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A journal devoted to rocket technology and the jet propulsion field

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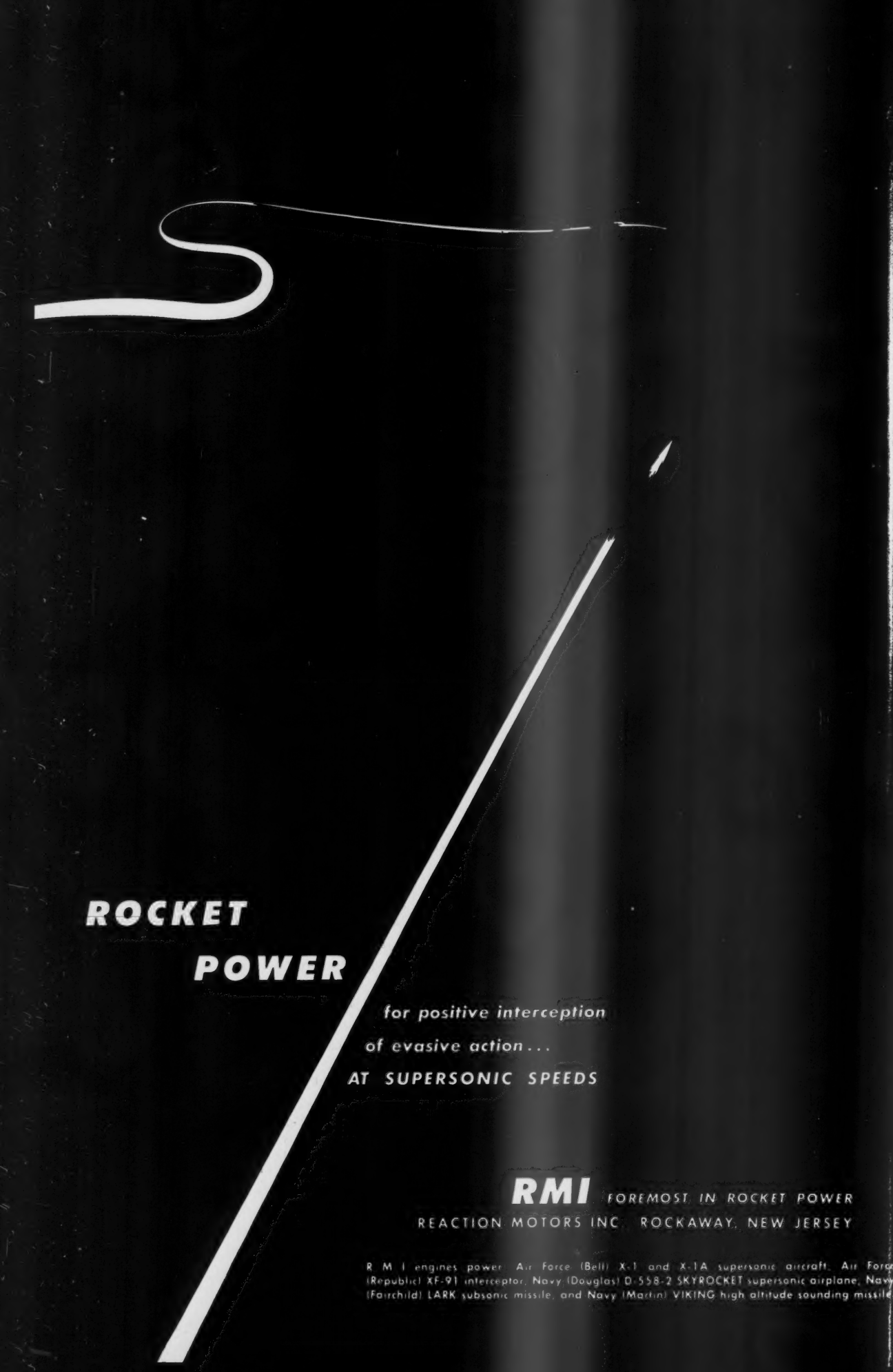
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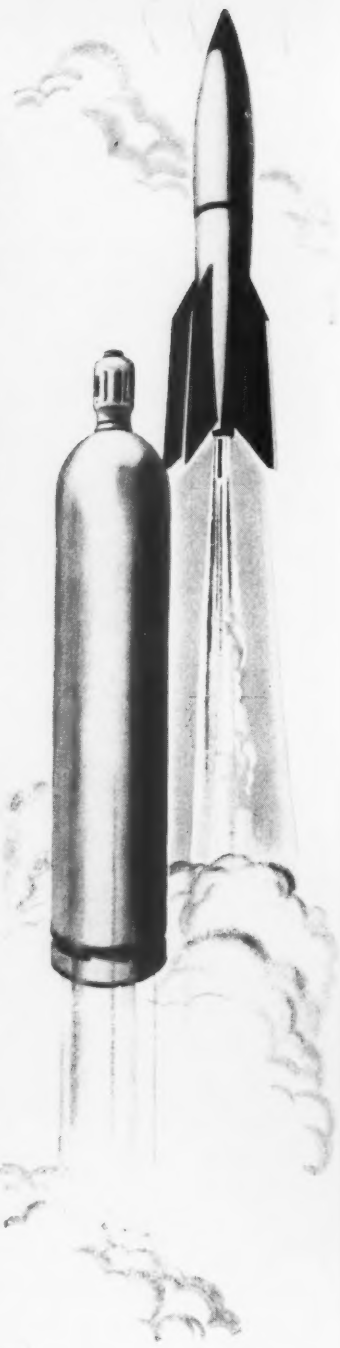

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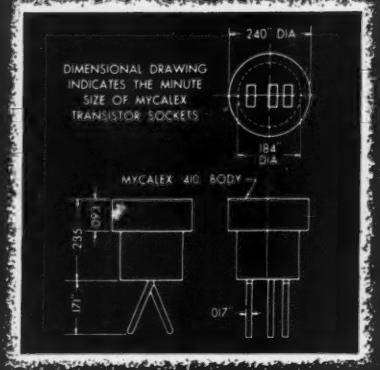

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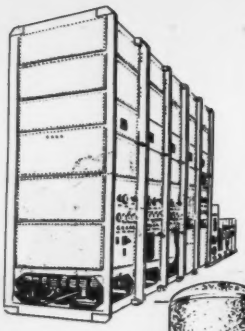

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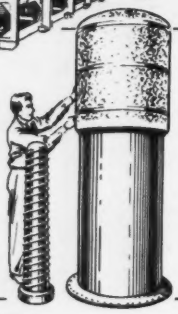

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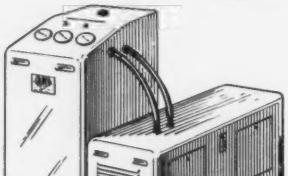

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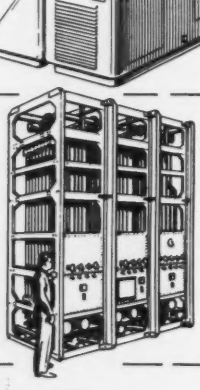

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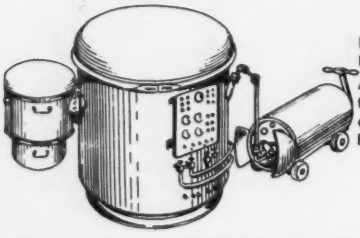

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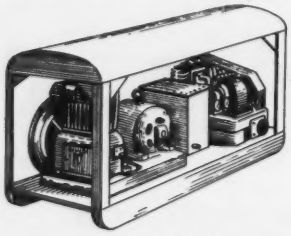

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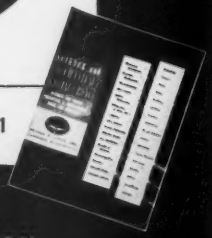

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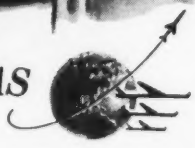
Depend on *DOUGLAS*  **First in Aviation**

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JANUARY-FEBRUARY 1953
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JOURNAL OF THE AMERICAN ROCKET SOCIETY

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Rocket Upper Air Research[1]

HOMER E. NEWELL, JR.,[2] and JOSEPH W. SIRY[3]

Naval Research Laboratory, Washington, D. C.

Among the most interesting and important phenomena associated with the high atmosphere are the ionosphere, behavior of the earth's magnetic field, and the aurorae. None of these is satisfactorily explained as yet. Of vital importance in formulating adequate theories for such phenomena, and for the atmosphere in general, is knowledge about air densities, motions, and composition, magnetic field strengths, incoming electromagnetic and particle radiations, and the airglow at all altitudes into and beyond the F region. Many of these quantities cannot be observed at all from the earth or from balloons. Others have been estimated with insufficient accuracy by inference from surface measurements. But rocket-borne instruments can observe and measure directly these very important quantities. Densities have been obtained to 219 kilometers above White Sands, N. Mex., where a density within 20% of 10^{-7} gm/m^3 was observed. An 80 ± 20 m/sec wind was measured at 200-kilometer altitude. A tendency toward diffusive separation of He, Ne, and A has been observed near 70 kilometers, in contradiction to strong and clear-cut theoretical arguments against such an occurrence. Ozone has been measured to 70-kilometer heights, where a particle density of 3×10^{-7} relative to the surrounding air was observed. The known solar spectrum has been extended in detail to 2000 A, and the atmospheric penetration of selected wave-length regions down to soft x-rays has been studied. A rocket measurement has indicated that the hitherto quoted value of 0.131 watt/cm^2 for the solar constant is 5 per cent too low. Ion and electron density curves have been obtained from the D region at 60 kilometers up to 380 kilometers in the F region. Current sheets have been observed in the E region at a time when the variation in the surface value of the earth's magnetic field showed a maximum. But only a beginning has been made in the field of rocket upper air research. To exploit the rocket technique to the fullest, firings must be conducted at various geographic locations, and the experimenter must have missiles capable of exceeding 500-kilometer altitudes.

MUCH of upper air research has been a great effort to overcome man's inability to go into the high atmosphere and make direct observations there. Working at or near the earth's surface the upper-air physicist has assembled vast stores of data on the aurorae, the earth's magnetic field, propagation of sound and radio waves in the atmosphere, transmission and absorption of solar radiations, airglow, meteors, and cosmic rays (1, 2).[4] Out of this store of information he has attempted to deduce the physical state of the high atmosphere, its density, pressure, temperature, composition, and motions, to explain the formation of the ionosphere and its behavior, to provide satisfactory theories of the aurorae and of variations in the earth's magnetic field, and generally to understand the atmosphere and phenomena associated with it. At present most of the interesting phenomena in the high atmosphere are yet to be fully explained.

There has always been an effort to get measuring apparatus into the upper atmosphere, in order to make as direct a contact as possible with the object of study. In 1749, for example, Dr. Wilson of Glasgow used kites to measure air temperatures. Toward the end of the same century the balloon became available for such research and for the last fifty years has been used extensively. Some of the balloons flown for research purposes were manned, the most notable such flight being that of Explorer II in 1935 to a height of almost 14 miles. Most sounding balloons, however, were and are unmanned. Airplanes have also been used for research flights, but until 1945 the free balloon, with a peak altitude of around 30 kilometers, remained the highest flying research vehicle available. Now improved balloons have exceeded 40 kilometers in altitude, and rockets reach the F region of the ionosphere.

The sounding rocket has succeeded in picking up where the balloon leaves off. There are many rocket results in which more confidence can be placed than in previous indirect inferences. Some of the observations, such as those of ultraviolet and x-ray sunlight, could not be made from the earth's surface or from balloons.

The most extensive set of rocket upper-air measurements are those of pressures, densities, temperatures, and winds. These were made in V-2's, Aerobees, and Vikings by various agencies of the Department of Defense. Except for one firing on the equator at 160 deg W, the rockets were all launched at White Sands, N. Mex.

R. J. Havens and his colleagues at NRL used bellows, Pirani, Philips, and Havens cycle gages (3) to measure pressures at the nose and on the sides of a moving rocket. From these fundamental data they calculated ambient atmospheric pressures, densities, temperatures, and winds (4, 5, 6).

Ambient atmospheric pressures were obtained directly from readings taken on the sides of rockets just ahead of the

[1] Presented at the Fall Meeting of the AMERICAN ROCKET SOCIETY, Chicago, Ill., September 9, 1952.
[2] Head, Rocket-Sonde Research Branch.
[3] Theoretical Physicist, Rocket-Sonde Research Branch.

[4] Numbers in parentheses refer to the References on pp. 12–13.

tail fins. Wind tunnel tests and comparisons between rocket and balloon measurements below 30 kilometers showed that the observed pressures would be equal within experimental error to the ambient atmospheric pressures. Fig. 1 shows the results of four separate flights at White Sands during winter. The pressures shown are correct to within 10 per cent. Deviation from the average is less than the experimental error. Fig. 2 shows summer pressure data of similar accuracy, except for the 82.4-kilometer point, for which the probable error is indicated. The solid curve of Fig. 1 is repeated as a dashed curve in Fig. 2, showing that winter and summer curves differ only in the neighborhood of 65 kilometers, where the separation is a factor of four greater than the estimated probable error. The May 11, 1950, data were obtained above the equator at 160 deg W, and show no very great difference from White Sands conditions. Similar pressure measurements were also made up to 122 kilometers, but above 75 kilometers the values could be in error by a factor of 2. Within this error, the pressure over White Sands on both March 7, 1947, and January 22, 1948, at 122 kilometers above sea level, was determined to be 3.5×10^{-5} mm of Hg.

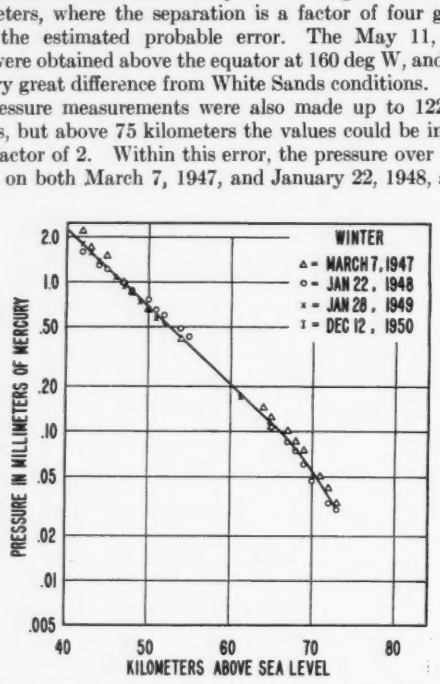

FIG. 1 WINTER PRESSURES OVER WHITE SANDS, N. MEX.

The Dec. 12 pressure was measured at midnight; the other pressures were measured at daylight.
(Courtesy of *Journal of Geophysical Research*, Ref. 4)

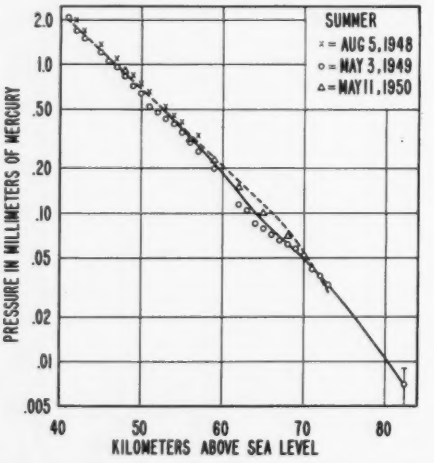

FIG. 2 SUMMER PRESSURES OVER WHITE SANDS, N. MEX., AND OVER THE EQUATOR NEAR CHRISTMAS ISLAND, PACIFIC OCEAN

The Aug. 5, 1948, and May 3, 1949, data are for White Sands; the May 11, 1950, data for the equator. The dashed line shows the average winter pressure for comparison.
(Courtesy *Journal of Geophysical Research*, Ref. 4)

Below 100 kilometers the density ρ of the atmosphere was calculated from the stagnation pressure P measured at the nose of a yawless supersonic rocket by means of the formula

$$\rho = 0.144 \frac{P}{V^2} - \frac{0.066}{V^2} p + \ldots$$

obtained from Rayleigh's formula by setting the ratio of specific heats of the air equal to 1.4. The quantity V is the speed of the rocket, and p is the ambient atmospheric pressure. On the right, the second and succeeding terms are negligible in comparison with the first. Errors are introduced by yawing of the missile, but if the rocket is moving sideways and rolling, ρ can be obtained with moderate accuracy by letting P be the total pressure change occurring on one side of the rocket during a single roll.

Above 110 kilometers, where the mean free path becomes comparable to the size of the rocket, densities were calculated from the equation

$$\rho = \frac{0.182\ \Delta P}{V_1}, \qquad [\text{gm m}^{-3};\ \text{mm Hg};\ \text{km sec}^{-1}]$$

This formula was derived from simple kinetic theory. In it ΔP is the total change in pressure, during one roll, in a gage on the side of a rolling rocket, and V_1 is the rocket velocity normal to the gage opening.

Densities determined from six rocket flights are shown in Fig. 3. Except for the May 11, 1950, flight at the equator, the data were taken above White Sands in New Mexico. The probable errors below 80 kilometers are less than 20 per cent. The highest altitude values for January 22, 1948, are lower bounds to the actual densities, but are probably correct to within a factor of 2. On August 7, 1951, at 1104 MST the density at 219 kilometers above sea level over White Sands was found to be within 20 per cent of 10^{-7} gm/m^3 (5).

All the pressure and density data obtained on the various flights can be combined to provide an average set of values for the high atmosphere. Using the gas law and the hydrostatic equation, a temperature-altitude curve for this average atmosphere can be calculated. Such a curve is shown in Fig. 4. Note that the temperature maximum in the neighborhood of 50 kilometers is 270 K, much lower than ground-based experiments had previously indicated. The solid curve is based on sea-level atmospheric composition which is expected to exist up to 80 kilometers. Above 80 kilometers, oxygen be-

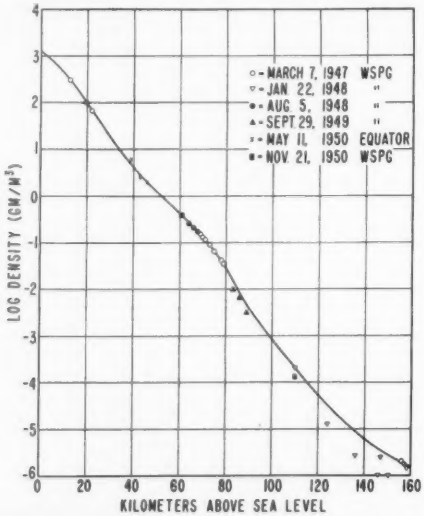

FIG. 3 ATMOSPHERIC DENSITIES OVER WHITE SANDS, N. MEX., AND OVER THE EQUATOR NEAR CHRISTMAS ISLAND, PACIFIC OCEAN. VALUES FOR JAN. 22, 1948, ARE MINIMUM DENSITIES
(Courtesy *Journal of Geophysical Research*, Ref. 4)

gins to dissociate due to absorption of ultraviolet sunlight. The transition from all molecular to all atomic oxygen occurs between 80 and 120 kilometers, as was verified by Friedman and co-workers in a September, 1949, rocket flight. Calculations show that a similar transition of nitrogen from all molecular to all atomic should occur between 100 and 200 kilometers. Such dissociations have a pronounced effect upon the average molecular weight of the gas comprising the atmosphere, with a corresponding effect upon the temperature deduced from measured densities. The dotted curve in Fig. 4 is speculative, but is consistent with Havens' measured densities under the assumption that the average molecular weight of the air changes linearly from 29 at 80 kilometers to 14.5 at and above 200 kilometers.

A different technique for measuring temperature in the region from 30 to 80 kilometers has been used by M. J. Ference, of the Signal Corps Engineering Laboratories, and his co-workers (7). These measurements were made with Aerobees fired from the White Sands Proving Ground at night. Grenades were ejected from the flying rockets, and exploded. The explosions were photographed at carefully fixed positions on the ground. From these pictures the positions in space of the explosions were determined very accurately. Each explosion was carefully timed, as was the arrival of the sound at each of five listening stations arrayed 1000 feet apart along the legs of a right triangle directly below the rocket. The angle of arrival of the wave front at each station was also determined. From these data, winds and the speed of sound in the upper air could be calculated. Knowing the speed of sound, the temperature could be deduced to better than 8 K.

Ference's results are in good agreement with those of Havens, showing a temperature maximum in the neighborhood of 50 kilometers, considerably lower than those obtained from the early ground-based experiments. They

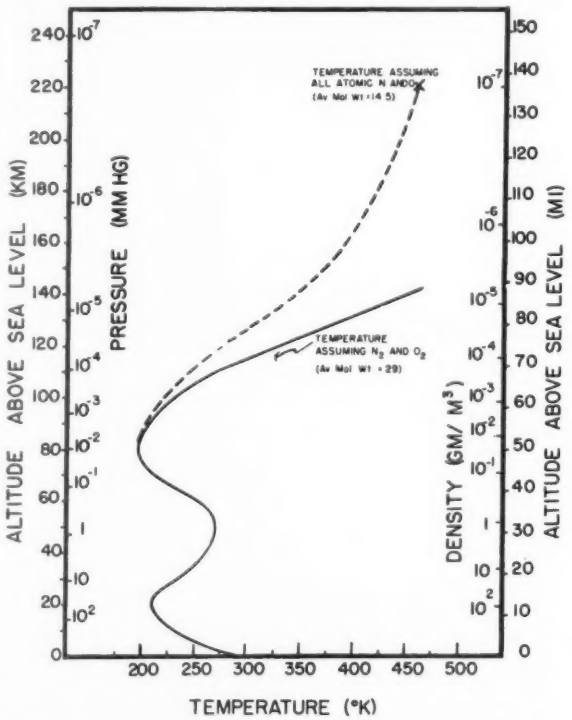
ALTITUDE ABOVE SEA LEVEL (KM)
PRESSURE (MM HG)
DENSITY (GM/M³)
ALTITUDE ABOVE SEA LEVEL (MI)
TEMPERATURE (°K)
TEMPERATURE ASSUMING ALL ATOMIC N AND O
(Av Mol Wt = 14.5)
TEMPERATURE ASSUMING N2 AND O2
(Av Mol Wt = 29)

FIG. 4 ATMOSPHERIC TEMPERATURES ABOVE WHITE SANDS, N. MEX.

Calculated from various pressure and density data published by Havens and co-workers. Solid curve based on sea-level composition. Dashed curved speculative, assuming a linear transition of oxygen and nitrogen from all molecular at 80 km to all atomic at and above 200 km.

also indicate very low temperatures near 80 kilometers. High-speed winds were observed at these levels. It is understood that the Signal Corps results will be published in the very near future.

The University of Michigan has used still another method to evaluate air temperatures (8). From the ratio of pressures observed at two distances from the nose, one can estimate the Mach number of the flow past the rocket, which in turn yields the speed of sound in the ambient atmosphere. The temperature can then be calculated from

$$a^2 = \gamma \frac{R}{M} T$$

where a is the speed of sound; γ is the ratio of specific heats of the gas; R, the universal gas constant; M, the average molecular mass of the air; and T, the absolute temperature. Atmospheric temperature curves obtained in this fashion by Sicinski and Spencer (9) are in good general agreement with those of Havens and Ference.

A summary of all the rocket upper-air data on atmospheric temperatures, densities, and pressures obtained so far has been prepared in the form of average values for these parameters. A table of these quantities is soon to be published jointly by the Upper Atmosphere Rocket Research Panel.

The observation of meteor trains shows that rapid winds exist between 30 and 100 kilometer heights. Ference's rocket measurements confirm these conclusions, and a single Viking flight extends wind measurements to the F region of the ionosphere. On the flight of August 7, 1951, it was noted that the relative wind blowing past the rocket was displaced from the direction of rocket motion. This shift was assumed to be due to horizontal atmospheric winds, the calculation of which is still under way. Havens and Spitz have already determined, however, that the horizontal wind at 200 kilometers was 80 ± 20 m/sec from the southeast (6).

An atmosphere without mixing processes in operation would tend toward a state of diffusive equilibrium in which the heavier gases would settle to the bottom, the lighter gases predominating at the top. The diffusion proceeds much more rapidly at the higher levels where the density is low, so that in a quiet atmosphere, completely mixed originally, pronounced diffusive separation should first be noticeable at the top. For example, above 160 kilometers in a 273 K atmosphere, noticeable helium separation would occur in a matter of minutes, whereas below 100 kilometers the air would remain thoroughly mixed for years (10). Since the atmosphere below 100 kilometers is not quiet, no diffusive separation should occur.

But such separation of atmospheric gases has been observed in rocket flights at White Sands, conducted by M. H. Nichols of the University of Michigan and his co-workers. On each of a number of firings, several evacuated steel bottles were carried aloft, and opened and resealed automatically at various altitudes. Precautions were taken to insure that the air samples obtained were not contaminated by gases from the missile. After being retrieved from the fallen rocket, the samples were analyzed by Paneth (11–13) in England and by Nichols (14, 15) at Michigan, to determine the variation, if any, in the ratios of helium, neon, and argon to nitrogen. Most of the flights revealed no significant change in these ratios; but on two flights distinct increases in the He/N_2 and Ne/N_2 ratios and a small decrease in A/N_2 were found between 64 and 72 kilometers. In view of the clear-cut arguments against the occurrence of diffusive separation at these levels, this result requires some explaining, and further measurements of this sort will be watched with interest.

Light and particles radiated by the sun play a leading role in the activity of the earth's atmosphere. But those radiations which do have an important part in upper air physics impart their energy to or exert their influence upon the atmosphere by being absorbed at high altitude. They are accordingly

prevented from reaching the observer at the surface of the earth, who must attempt to deduce their nature and intensities from whatever effects he can observe through secondary radiations, radio, and sound.

A familiar example is found in the sunlight below about 2900 A. Shorter wave lengths are cut out of the sun's radiation by absorption before reaching the ground. Hence, in addition to their intrinsic interest for the student of the sun, these wave lengths have an especial interest for the geophysicist because of the roles they play in the atmospheric processes which remove them from the sunlight. In fact, one of the most important problems before the upper-air physicist today is to find out at what altitudes the different wave lengths are absorbed and to measure the incident intensities before any absorption has occurred. Complete data of this sort together with an accurate density-altitude curve and a knowledge of atmospheric composition will go a long way toward enabling the theorist to formulate a correct theory of the upper atmosphere in general and of the ionospheric regions in particular. The sounding rocket has provided the first opportunity in history to observe and measure the hitherto hidden sunlight.

Tousey, Purcell, and Johnson (16–18) of the Naval Research Laboratory, and Hopfield and Clearman (19) of the Applied Physics Laboratory, have used rocket-borne spectrographs to obtain solar spectrograms at various altitudes. By this means they have extended the known solar spectrum down to about 2000 A, and are continuing the experiments in an effort to reach even shorter wave lengths, in particular the Lyman alpha line of hydrogen at 1216 A. The series of spectra shown in Fig. 5 (18) are arranged in order of increasing altitude, and illustrate the effect of atmospheric constituents, in this case ozone, in removing sunlight by absorption.

Burnight, Friedman, Tousey, Watanabe, and others at NRL have used photographic emulsions, thermoluminescent coatings, and photon counters behind appropriate filters

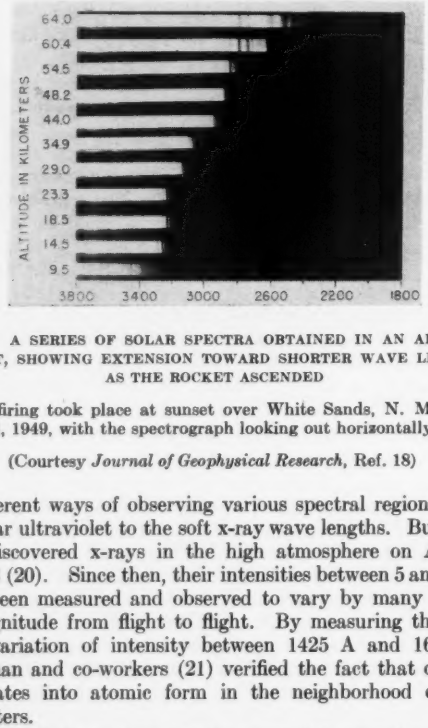

FIG. 5 A SERIES OF SOLAR SPECTRA OBTAINED IN AN AEROBEE ROCKET, SHOWING EXTENSION TOWARD SHORTER WAVE LENGTHS AS THE ROCKET ASCENDED

The firing took place at sunset over White Sands, N. Mex., on June 14, 1949, with the spectrograph looking out horizontally at the sun.

(Courtesy *Journal of Geophysical Research*, Ref. 18)

as different ways of observing various spectral regions from the near ultraviolet to the soft x-ray wave lengths. Burnight first discovered x-rays in the high atmosphere on August 5, 1948 (20). Since then, their intensities between 5 and 10 A have been measured and observed to vary by many orders of magnitude from flight to flight. By measuring the altitude variation of intensity between 1425 A and 1650 A, Friedman and co-workers (21) verified the fact that oxygen dissociates into atomic form in the neighborhood of 100 kilometers.

Results of the various attacks upon this general problem are shown in Table 1 and Fig. 6 (16, 18, 20–22). Only a beginning has been made. Gaps must be filled in, good

TABLE 1[a] SUMMARY OF ROCKET OBSERVATIONS ON SOLAR RADIATIONS ENTERING THE EARTH'S ATMOSPHERE

Wave length (Angstroms)	Approximate depth of penetration (kilometers)	Approximate altitude at which appreciable absorption begins (kilometers)	Approximate ratio of maximum intensity observed to intensity of 6000° K blackbody
2400	35	60	$1/6$
1425–1650	95	155	$1/200$
1100–1350	70	140	$1/100-1$
795–1050	90	125	10–100
5–10	87	145	Many orders of magnitude greater than one

[a] Based on Refs. 16, 20–22.

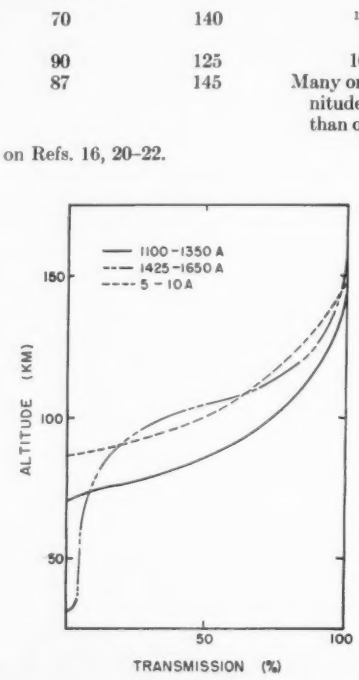

FIG. 6 PENETRATION OF THE ATMOSPHERE BY ULTRAVIOLET AND SOFT X-RAY SUNLIGHT OBSERVED IN A V-2 FLIGHT OVER WHITE SANDS, N. MEX., ON SEPT. 29, 1949
(Courtesy *Physical Review*, Ref. 21)

wave-length resolution obtained, and accurate measurements of intensity made. For the theorist, some of the most valuable information is that yet to be obtained in the F region at and above 300 kilometers. Also very important in the physics of the atmosphere, and probably of the weather, are temporal changes in ultraviolet and x-ray sunlight, changes about which little is yet known.

For the geophysicist a basic physical constant is the total power received at the earth in sunlight. From ground and balloon measurements in the infrared and visible regions of the sun's spectrum, this solar constant has been estimated as 0.131 watt per square centimeter. But a recent rocket experiment by A. L. Quirk of Rhode Island State College (23) indicates that the true value is about 5 per cent higher. It will be of interest to watch for further measurements of this sort.

A series of spectra like those of Fig. 5 can be used to obtain a distribution curve for the absorbing agent, which in this case was ozone. The ratio of spectral intensities at two different wave lengths in the absorption region is a function of the total ozone between the spectrograph and free space, and the variation of such a ratio with height can be used to calculate a curve of height versus total ozone vertically above that height. This curve can then be differentiated to give ozone concentration versus height. Such data obtained by Tousey and his colleagues (17, 18) are shown in Fig. 7. The

maximum concentration relative to the surrounding air occurs near 30 kilometers, but the greatest part of sunlight absorption takes place at higher altitudes. Above 55 kilometers very little ozone remains, about 0.003 mm at NTP.

If one is interested solely in determining ozone, one need not obtain complete photographic spectra. Instead, appropriate intensity ratios in the absorption region can be measured in the rocket photoelectrically and electronically, and this information sent to the ground by radio telemeter. This is the approach taken by Van Allen at APL (24) (now at the State University of Iowa). Van Allen shows a maximum ozone concentration above White Sands on January 25, 1951, at above 40 kilometers (25). One expects the height of maximum ozone concentration to depend greatly on meteorological conditions, but the difference between Tousey's and Van Allen's results is remarkable.

The various ionospheric layers are closely linked with solar radiation absorbed in the atmosphere. Equally important with learning where and in what quantities sunlight is absorbed in the atmosphere, is knowing what that absorbed

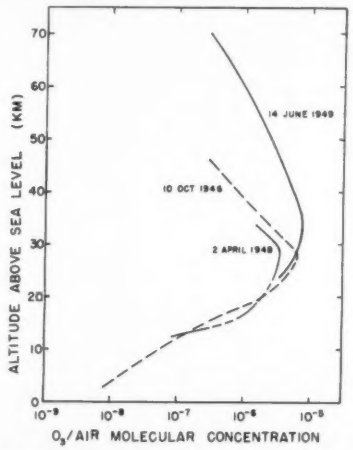

FIG. 7 OZONE CONCENTRATIONS OBSERVED ON A NUMBER OF ROCKET FLIGHTS OVER WHITE SANDS, N. MEX.
(Courtesy *Journal of Geophysical Research*, Refs. 17, 18)

energy does upon absorption and what its subsequent history is. Identifying the charged particles and determining their individual concentrations as a function of height in the ionosphere should go a long way toward understanding the role of solar energy in ionospheric physics.

It is possible with ground measurements, e.g., with the Breit-Tuve radio pulse techniques (1, chap. VI) to determine effective electron densities in the ionosphere at what are termed virtual heights. One cannot, however, determine the precise nature of the charged particles. Also virtual heights must be reduced to actual heights by applying some suitable theory, usually involving many assumptions. Moreover, a region of high effective electron density shields higher altitude regions of lesser effective electron densities from ground-based observations. With rockets, however, one can determine the nature of the charged particles, and can measure directly their individual concentrations versus actual height at all altitudes reached by the missile.

An important class of rocket experiments is based upon the fact that a radio signal is delayed in phase by the ionosphere. In various ways such phase delays can be used to give a measure of ion concentrations. On February 24, 1949, Berning (26) used one such technique to measure effective electron densities in the F region from 170 to 380 kilometers. This was on the occasion of the famous Bumper Wac firing, in which the Army launched a Wac Corporal from the nose of a flying V-2. Since, in the F region, effective electron density and actual electron density should be about the same, Berning's curve, shown in Fig. 8, presumably gives the distribution of actual electron concentration with height.

Using a different form of the same basic technique, J. C. Seddon (27) has obtained a number of ion distribution curves through the E region. These are to be published shortly.

One thing about the ionosphere that impresses the observer is its variability. Hence the small amount of rocket data obtained so far is the merest beginning in the gathering of sufficient information to understand all that goes on there.

Daily variations in the earth's magnetic field can be explained as the effect of current sheets in the E region of the ionosphere. The presence of such a current sheet, however, remained purely an assumption until it was actually detected in a rocket flight. Singer, Maple, and Bowen (28) measured the magnitude of the earth's field with a total field magnetometer carried aloft in Aerobees fired from the geomagnetic equator off the coast of Peru. At this location any magnetic field due to a current sheet would be roughly parallel to the earth's field, which is horizontal. Hence a marked change in total field should be observed in penetrating the current sheet if it exists, and no change should be seen if the current sheet does not exist. The measured fields from two flights are shown in Figs. 9 and 10. The former refers to a flight made when the diurnal field change was small, the latter to a flight made when the diurnal variation was near a maximum. No great change in field intensity gradient was observed in the first case, but a pronounced break in the second experimental curve appears at 93 kilometers. Thus the current sheet theory of diurnal magnetic variations has received qualitative support; but since the rocket probably did not completely penetrate the current sheet in the experiment of Fig. 10, quantitative verification awaits further such experiments to higher altitude.

It will be of great interest to continue study of ionospheric current sheets into and above the F region. Actually this problem is probably one of the most clear cut of the many magnetic field problems facing the geophysicist today. Those magnetic field effects associated with solar activity and the aurorae offer a great challenge to the rocket experimenter, and are inextricably linked with the general atmospheric pic-

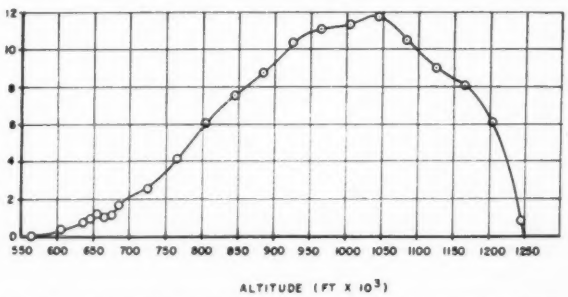

FIG. 8 ELECTRON DENSITY AS A FUNCTION OF ALTITUDE OVER WHITE SANDS, N. MEX., AT 2222 GCT, FEB. 24, 1949. ION DENSITY (ELECTRONS PER $M^3 \times 10^{11}$)
(Courtesy *Journal of Meteorology*, Ref. 26)

ture. At the present time the principal need is for many measurements to as high as possible.

Some cosmic ray work has been done in rockets. The rocket, however, is not an ideal vehicle for cosmic ray studies because of its short flight time, wobbling, and considerable structural mass. For many experiments the balloon with its hours-long stay at maximum height is a far better vehicle. Nevertheless, some interesting rocket results have been obtained.

Experiments on cosmic rays fall roughly into two classes: (*a*) those concerned with the geophysical and cosmic aspects of the rays, their identity, energy distribution, and origin; and (*b*) those which use the rays for nuclear studies. In the former group of studies, Van Allen and his colleagues at APL have determined the vertical primary cosmic-ray intensity at various geomagnetic latitudes (29). These results are shown in Table 2.

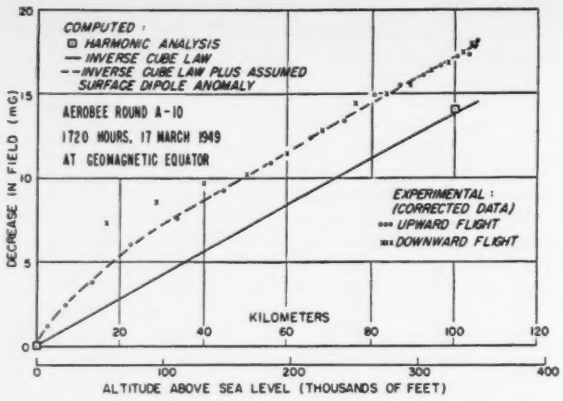

FIG. 9 DECREASE OF EARTH'S MAGNETIC FIELD OVER THE GEOMAGNETIC EQUATOR VS. ALTITUDE ABOVE SEA LEVEL AT TIME OF SMALL VARIATION IN SEA LEVEL FIELD
(Courtesy *Journal of Geophysical Research*, Ref. 28)

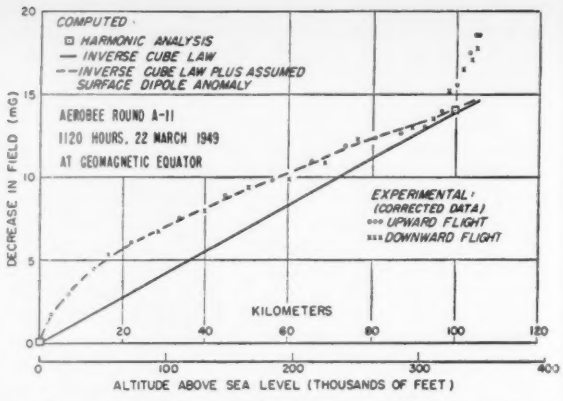

FIG. 10 DECREASE OF EARTH'S MAGNETIC FIELD OVER THE GEOMAGNETIC EQUATOR VS. ALTITUDE ABOVE SEA LEVEL AT TIME OF MAXIMUM VARIATION IN SEA LEVEL FIELD
(Courtesy *Journal of Geophysical Research*, Ref. 28)

TABLE 2[a] VARIATION OF VERTICAL COSMIC RAY INTENSITY WITH GEOMAGNETIC LATITUDE AS DETERMINED BY ROCKET EXPERIMENTS

Geomagnetic latitude (°N)	Experimental vertical intensity (sec cm² steradian)$^{-1}$
0	0.028 ± 0.004
41	0.073 ± 0.006
50	0.18 ± 0.02
58	0.29 ± 0.03

[a] Taken from Ref. 29.

At the geomagnetic equator the total unidirectional intensity j was found to vary with zenith angle θ according to the law

$$j = 0.028\,(1 + 0.6 \sin \theta)$$

counts per sec-cm²-steradian (30).

Looking for primary cosmic gamma rays, Perlow at NRL (31, 32) found that in the range from 3.4 to 90 Mev, such rays comprise only one part in 1300 of the total energy flux. During a V-2 flight at White Sands, N. Mex., geomagnetic latitude 41 °N, on February 17, 1950, Perlow and his colleagues (33) attempted to identify and measure the intensities of different components of the cosmic radiation by measuring both the specific ionization and the penetration capabilities of each particle. About ten per cent of the total radiation observed was a low energy albedo of slow electrons, protons, and alpha particles. The primary radiation intensity was found to be 0.070 ± 0.005 particle per cm²-sec-ster, consisting almost entirely of protons and alpha particles in the ratio of 5.3 ± 1.0 protons to one alpha particle.

The problems still before the rocket experimenter greatly outnumber the few answers he has obtained so far. The densities at 220 kilometers are an order of magnitude or more lower than had been supposed. A very important question for the theorist is how the density falls off at still higher altitudes, for on the answer depends where he will expect to find the sunlight absorption which is responsible for the F layers of the ionosphere. Then, when the absorption regions have been determined experimentally, the theorist will be in a position to check theory against fact. The matter of temperatures above the E region remains speculative, but is becoming clearer. In this connection, and in the more important matter of understanding the various ionospheric processes, the chemical composition of the atmosphere throughout the ionosphere is an essential factor. Not only major constituents like oxygen and nitrogen, but minor ones like H_2O, OH, NO, CH, CN, and Na must be determined. So far, rocket composition results do not reach above the E region. One awaits with interest the extension of such measurements into the F region.

The ion and electron concentration measurements must be made again and again. The role of micrometeorites, those tiny particles and molecular aggregates which sweep through the atmosphere continuously, should be examined. Also the rocket has not yet been put to use in the highly active and very important field of auroral physics. It seems that much could be learned by observing photon and particle radiations within an auroral display. Both day and night airglows result from atmospheric activity, and knowledge of the sources and absolute intensities of these radiations should be a key to many mysteries. At present, estimates of the altitude from which a specific radiation emanates may differ by hundreds of kilometers. Rocket observations, however, can pin down once for all the heights of the different airglow sources. Work in this important field has only just begun, and should be extended and vigorously pushed. H. A. Miley and co-workers at the Air Force Cambridge Research Center (34) have measured daytime airglow intensities at rocket altitudes, and between 40 and 130 kilometers find very high, rather constant intensities in the blue and the green wave lengths. Miley's results are sufficiently surprising that one prefers to wait for further such measurements before quoting numbers.

Winds, turbulence, general circulation patterns, rates of diffusion and mean free paths for different particles, and the general dynamic activity of the high atmosphere are interesting and should be fruitful objects of rocket study. Many of these factors enter in a significant way into the formation and positioning of the ionosphere, and into observed magnetic field phenomena. The earth's magnetic field must be measured at various latitudes to as high as possible.

To make the important measurements now feasible with rockets, firings at various geographic locations are essential. One must especially go into the northern latitudes and to the geomagnetic and geographic equators. Also, to cover adequately the F region, which is the scene of some of the most interesting, fundamental, and challenging phenomena, measuring equipment must be capable of reaching 500-kilometer heights. When the rockets do reach and begin to exceed such heights, the experimenter will of course find himself trying to observe what he can in interplanetary space. But before that time, the most fascinating and fruitful period in the history of rocket upper air research is yet to be lived.

The authors wish to thank Miss E. Pressly for assistance in assembling references and for preparing some of the figures.

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Physical Mechanics, a New Field in Engineering Science

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The purpose of physical mechanics is to predict the engineering behavior of matter in bulk from the microscopic properties of its molecular and atomic constituents. The constants and basic concepts of this new engineering science, of particular importance to rocket and jet propulsion, are discussed in this paper.

THE term physical mechanics has been used in the past to indicate a course in classical mechanics for sophomores and juniors in college (1).[2] Physical mechanics here is used to designate a new field in engineering science, the purpose of which is to predict the macroscopic behavior of matter, of interest to engineers, from the known microscopic properties of the constituents of matter. The need for such a branch of science arises originally from the advanced engineering problems in jet propulsion, aeronautics, and atomic power, but impact of this new discipline is inevitable on all fields of engineering. This article will discuss the contents of physical mechanics and its point of view. Above all, the purpose here is to attract the attention of scientists and engineers to this new and fruitful field.

Basic Concepts

The constituents of matter are molecules and atoms. The atom, in turn, consists of a central nucleus and an electron cloud surrounding the nucleus. According to the prevailing view, the nucleus is ultimately made up of protons and neutrons. This relentless drive of physicist to the "heart" of the matter was perhaps motivated by the desire to interpret all nature phenomena by a unified theory from the elementary structures. During this development of physical science in the past century, there was a continuous interplay between two phases of the study. One phase was the investigation of the structure of molecules and atoms by analytical procedures such as x-ray analysis and electron diffraction, molecular and atomic spectroscopy. The other phase was the explanation of the bulk properties of matter such as heat capacity, the pressure of fluids, from the molecular and atomic structure. The second phase of the investigation, developed by the use of the statistical mechanics and the kinetic theory, was of particular importance to the physicist and the chemists in that the earlier pictures of the molecular and atomic structures were quite uncertain and vague. Therefore the physical scientists needed the comfort of seeing their theory verified by "every-day" experience with matter in bulk.

The present knowledge of the molecular and atomic structures is, however, very complete and well founded. To the physical scientists then, the interpretation of the macroscopic behavior of matter from the atomic theory is only of side interest. A physicist's main interest is one step deeper: The structure of atomic nuclei and the properties of their constituent elementary particles. This situation in physics and chemistry leads naturally to a reversal of the procedure. The statistical mechanics and the kinetic theory are not used to verify the atomic theory through the bulk properties of matter, but rather should be used to predict the bulk behaviors of matter from the known properties of the molecules and atoms. Since engineers always deal with matter in bulk, the prediction of bulk properties is then of vital interest to engineers, and is logically a branch of engineering science.

However, it might be argued that the mere fact of the engineer's interest in bulk properties of matter does not necessarily mean the need for physical mechanics. The bulk properties can be measured directly; then the theoretical calculations of physical mechanics will not be needed. This has been the situation till very recently. When the engineer needs the thermodynamic properties of steam or ammonia, he measures them. When the engineer needs the viscosity of water, he again measures it. If such direct measurements can be made easily with the required accuracy, there is no incentive to introduce new methods. Recently, however, particularly with the advent of rocket and jet propulsion engineering and nuclear engineering, bulk properties of matter at unusual conditions are required. For instance, thermodynamic properties at very high temperatures, say, 4000°K, enter into engineering calculations. The experimental measurement of thermodynamic properties at such temperatures is certainly very difficult, if not impossible. On the other hand, the thermodynamic properties of gases at high temperatures can be calculated by the method of statistical mechanics with ease and certainty, once the properties of the constituent molecules and atoms are known. This circumstance can be easily understood by the observation that although the bulk temperature of the gas may be very high in the conventional engineering sense, the average energy of a single molecule or atom is quite moderate and within the range of certain knowledge of a physicist or a chemist. For instance, the average or representative kinetic energy of molecule or atom at a temperature T in the absolute scale is $3/2\ kT$, k being Boltzmann's constant. The value of k is given by

$$k = 1.380 \times 10^{-16} \text{ erg per } °\text{K}$$
$$= 0.861 \times 10^{-4} \text{ electron-volt per } °\text{K}$$

Therefore even at the "fantastic" temperature of 10,000°K, the average kinetic energy of the atoms is still only 1.292 electron-volt, an energy at which the behavior of atoms is known with accuracy.

Physical Mechanics as an Engineering Science

The problems in physical mechanics can be classified into two categories: Problems in thermodynamic properties of matter at equilibrium, and problems in transport properties of matter not at equilibrium. Although the powerful methods of statistical mechanics are equally as applicable to matter at thermodynamic equilibrium as to matter not at equilibrium, concrete useful results are obtained easily only for the first case. For the transport properties, such as viscosity, heat conduction, and diffusion, the methods of the kinetic theory of matter give quantitative answers.

Examples of the first category of problems are the thermodynamic functions of gases, solids and liquids, the equation of states for imperfect or highly compressed gases, chemical equilibrium constants, and the thermodynamic behavior of

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[2] Numbers in parentheses refer to the References on page 16.

electrically charged gases, such as gas containing ions and electrons. The previous investigations and results in this field are summarized, for example, in the two excellent books by Sir R. Fowler (2) and by Fowler and E. A. Guggenheim (3).

Examples of the second category of problems are, besides those already mentioned, the neutron diffusion in a nuclear reactor, and the moderation of fast neutrons from the fission nuclei to thermal neutrons by the reactor materials. Therefore many problems in nuclear engineering dealing with the macroscopic effects of elementary nuclear processes belong logically to the science of physical mechanics. The theory of transport properties of gases is given in the famous book by S. Chapman and T. G. Cowling (4). Besides those problems of transport properties, the radiative emissivity of gases at high temperatures and the spectra obtained from regions of active combustion are also important problems of the second category.

It is evident that there has been certainly no lack of effort by physicists and physical chemists in the general field of what is here called physical mechanics. Physical chemists were particularly diligent in carrying out many extremely tedious calculations (5). Then, is the task of establishing physical mechanics as an engineering science that of simply disseminating this work of physicists and chemists among the engineering profession? Unfortunately, the task is not as simple as that. To establish physical mechanics as an engineering science, one must follow the example of other branches of engineering science, such as fluid mechanics, by introducing the successful guiding principles of the so-called "angewandte Mechanik." These principles of engineering science were first formulated and applied by a group of brilliant "applied mechanicists" of Göttingen University at the turn of this century (6). The following sections will be devoted to a discussion of these principles as applied to physical mechanics.

Use of Approximate Models

One of the principles of engineering science is the approximate solution of complex problem by using a simplified model which gives a *satisfactory* representation of *reality*. Because of the very fact that the model is simple, it cannot have all the properties of the real system, and it can be only designed to emphasize the most important feature of the real system under the particular physical situation concerned. Under a different physical situation, the real system may very well reveal a different property which is important. Then a different model has to be adopted. Therefore the success of the choice of models rests on the clear understanding of the physical circumstances. A "physical mechanicist" can have, however, assistance in this difficult task in two ways. He can always study the experimental observations connected with the phenomenon and thus gain insight to the problem. Then he is helped by knowing the logical requirement, that the models representing the same physical system, although they may be different under different situations, should nevertheless be compatible with each other and should not be contradictory to each other. The following is an example for the point under discussion.

From diffraction experiments and spectroscopic studies, the structure of molecules can be determined in terms of interatomic distances and bond angles. Such data, together with the van der Waals sizes of atoms, then give a definite model of a molecule as a structure of spheres (atoms) properly fused together. At ordinary temperatures, the rotation of molecules in a gas is fully excited. Thus the odd-shaped molecule is really under rapid rotation, and for molecules that are not excessively elongated the angular asymmetry is averaged out. Therefore, when one is considering the interaction of molecules, as, for example, in the calculation of the second virial coefficient and the transport properties of gases, one may well consider the molecules as spheres with a diameter r^* equal to twice the maximum distance between the center of mass of the molecule and the boundary of the molecular model. This is shown to be actually the case by S. D. Hamann (7) and by Hamann and J. F. Pearse (8) for nonpolar molecules with the Lennard-Jones potential given by

$$\epsilon(r) = \epsilon^* \left[\left(\frac{r^*}{r}\right)^{12} - \left(\frac{r^*}{r}\right)^{6} \right] \quad \ldots\ldots\ldots\ldots [1]$$

where r is the distance between the centers of mass of the molecules, ϵ the interaction energy, and ϵ^* the interaction energy at the distance r^*, the equilibrium distance. This is a very satisfactory state of affairs, as the chosen model of molecular interaction is entirely compatible with a wide range of other physical phenomena and concepts.

For polar molecules with permanent dipole moment μ, W. H. Stockmayer (9) proposed an interaction potential which is a hybrid between the Lennard-Jones potential of Equation [1] and the dipole interaction potential,

$$\epsilon = \epsilon^* \left[\left(\frac{r^*}{r}\right)^{12} - \left(\frac{r^*}{r}\right)^{6} \right] - \frac{\mu^2}{r^3} \left[2 \cos\theta_1 \cos\theta_2 - \sin\theta_1 \sin\theta_2 \cos\varphi \right] \ldots [2]$$

where θ_1, θ_2, and φ are angles specifying the orientation of the interacting dipole axes. Following the work of W. H. Keesom (10), Stockmayer calculated the second virial coefficient $B(T)$, where T is the temperature, as

$$B(T) = \frac{1}{4} N \int_0^\infty r^2\, dr \int_0^\pi \sin\theta_1\, d\theta_1 \int_0^\pi \sin\theta_2\, d\theta_2 \times \int_0^{2\pi} [1 - e^{-\epsilon/kT}] d\varphi \ldots [3]$$

where N is Avogadro's number, ϵ is the interaction potential given by Equation [2], and k is Boltzmann's constant. The fitting of the experimentally determined second virial coefficients to Stockmayer's formula was carried out by J. O. Hirschfelder, F. T. McClure, and I. F. Weeks (11), and also by Hamann and Pearse (8) for methyl chloride and methyl fluoride. The results are, however, anomalous. For instance, the "size" r^* for steam and ammonia turns out to be approximately the van der Waals diameter of the oxygen atom and nitrogen atom, respectively, *alone*, without any room allowed for the hydrogen atoms in these molecules. It thus seems that Stockmayer's model of polar molecules is not entirely unquestionable.

An explanation of this difficulty can be obtained by observing the fact that if the molecule is under almost free rotation, then the dipole attraction and the dipole repulsion at any distance r between molecules average out by the prevailing random orientation. Consequently, when the rotation of molecules is fully excited, the dipole moment of the molecule makes no contribution to the interaction potential. In other words, as far as the calculations of the second virial coefficient and transport properties are concerned, it may be more realistic to neglect the difference between a polar molecule and a nonpolar molecule. This assumption will give a great simplification for the calculation of transport properties of polar gases. By fitting the second virial coefficient data for steam and ammonia to the formula for nonpolar molecules, satisfactory sizes r^* for these molecules are obtained. Of course, the validity of this point of view has yet to be proved by a critical examination of the theory of virial coefficients.

A Question of Methodology

In recent years, perhaps because of the influx of mathematicians to the field of applied mechanics, the level of logical organization and of mathematical argument of research papers in this field is generally quite high. This modern trend, by itself, contributes to the elegance of presentation and facilitates the general understanding of the work. However,

clarity of thought and the use of advanced mathematical tools have more than just this to contribute. In many problems of engineering science, the very complexity of the problems demands the most efficient and powerful tools for their solution. It is even to be expected that in many cases the problem will not be solved by any means other than the most efficient and powerful method. Therefore, to establish physical mechanics as an engineering science, it is necessary to emphasize this point of methodology.

As an example of lack of clarity of organization, one may take a recent paper (12) on the thermodynamic properties of completely ionized hydrogen. The criticism here is not that the results are incorrect, but rather that the same results could be obtained very simply and logically in a direct way. For this problem, one should first recognize that all thermodynamic properties of matter are contained in the partition function, or alternately, the free energy expression. Therefore the logical first step would be to establish the free energy of such ionized hydrogen, composed of equal numbers of positively charged protons and negatively charged electrons. But then the problem is exactly the same as the problem of solutions of electrolytes which dissociate into positive and negative ions. For solutions of electrolytes, there is the well-known Debye-Hückel theory.[3] The approximations involved and the validity of the assumptions involved in this theory are now clearly understood. By applying the Debye-Hückel theory to the problem of ionized hydrogen, one is at once clear about the power and the limitations of the solution. This alone is a worth-while saving in effort.

To show how easily the thermodynamics of completely ionized hydrogen can be determined with the rational method, one notes that if F is the free energy of the assembly, E the internal energy, V the volume, P the pressure, and T the temperature, then according to the general laws of thermodynamics

$$P = -\frac{\partial F}{\partial V} \quad [4]$$

$$E = -T^2 \frac{\partial (F/T)}{\partial T} \quad [5]$$

According to the Debye-Hückel theory,[3] the first approximation to the free energy of Coulomb interaction F^{el} of equal numbers of positively and negatively charged particles with $\pm ze$ charge on each particle is

$$F^{el} = -\frac{2}{3}\sqrt{\pi}\, NkT \left(\frac{N^{1/2} z^2 e^2}{V^{1/2} kT}\right)^{3/2} \quad [6]$$

where N is the total number of particles. Therefore, with Equations [4] and [5], the deviation ΔP of pressure and the deviation ΔE of internal energy from an assembly without Coulomb interaction are

$$\Delta P = -\frac{1}{3}\sqrt{\pi}\,\frac{NkT}{V}\left(\frac{N^{1/2} z^2 e^2}{V^{1/2} kT}\right)^{3/2} \quad [7]$$

$$\Delta E = -\sqrt{\pi}\, NkT \left(\frac{N^{1/2} z^2 e^2}{V^{1/2} kT}\right)^{3/2} \quad [8]$$

For ionized hydrogen, $z = 1$, and if H is the atomic weight of hydrogen, and ρ the density of the mixture

$$N/V = 2\rho/H \quad [9]$$

Therefore for ionized hydrogen

$$\Delta P = -\frac{\sqrt{\pi}}{3}\left(\frac{2\rho}{H}\right)^{3/2}\frac{e^3}{\sqrt{kT}} \quad [10]$$

and

$$\Delta E = -\sqrt{\pi}\left(\frac{2\rho}{H}\right)^{3/2}\frac{Ve^3}{\sqrt{kT}} \quad [11]$$

[3] See, for instance, Ref. 3, Chapter IX.

These results are the same as those in Reference 12 and are obtained here with very little calculation.

As an example of the advantages of mathematical technique in shortening the calculation, one may consider the second virial coefficient $B(T)$ for the Lennard-Jones potential of Equation [1]. It is known[4] that, with N as Avogardo's number, and

$$r_0 = 2^{-1/6}\,\sigma \quad [12]$$

$$\frac{B(T)}{\frac{2\pi}{3}Nr_0^3} = -\frac{1}{4}\left(\frac{4\epsilon^*}{kT}\right)^{1/4}\sum_{n=0}^{\infty}\frac{\Gamma\left(\frac{n}{2}-\frac{1}{4}\right)}{n!}\left(\frac{4\epsilon^*}{kT}\right)^{n/2} \quad [13]$$

This series, although convergent for all values of T, is nevertheless inconvenient for very small values of temperature. For instance, it is stated (5) that for $kT/\epsilon^* = 0.3$, about thirty terms are necessary to obtain an accuracy of five significant figures. The situation evidently calls for asymptotic expansion of the function $B(T)$ instead of the Taylor series of Equation [13]. The asymptotic series can be obtained easily as

$$\frac{B(T)}{\frac{2\pi}{3}Nr_0^3} \sim -\sqrt{\frac{\pi kT}{2\epsilon^*}}\, e^{\epsilon^*/kT} \times \sum_{n=0}^{\infty}\frac{\Gamma\left(n+\frac{3}{4}\right)\Gamma\left(n+\frac{5}{4}\right)}{\Gamma\left(\frac{3}{4}\right)\Gamma\left(\frac{5}{4}\right)n!}\left(\frac{kT}{\epsilon^*}\right)^n \quad [14]$$

This expression has not only the advantage of being easier to use at small values of T, but also the advantage of clearly demonstrating the exponential behavior of the function at low temperatures. Such definite indication of functional behavior is often a help in understanding the interactions of the different elements of a problem.

Concluding Remarks

In the preceding discussion, the subject matter and the basic concepts of the new engineering science, physical mechanics, are outlined. It is an engineering science mainly because its foremost purpose is to help solve the engineering problems. And since it is an engineering science, physical mechanics should be a subject of training for any research or development engineers, of equal importance with fluid mechanics and solid mechanics. Because of its close relation to jet propulsion and rocket development, physical mechanics is now taught as a graduate course at the California Institute of Technology in the Daniel and Florence Guggenheim Jet Propulsion Center. However, the course is open to students of other fields of engineering with the proper preparation in mathematics, physics, and chemistry.

To skeptical purists among physicists and physical chemists, this discussion may appear to be overly optimistic or even immodest. For them, the author can only point to the unquestionable success of fluid mechanics and solid mechanics in modern engineering. There is no reason to expect the future of physical mechanics to be radically different.

References

1 See, for instance, "Physical Mechanics—An Intermediate Test for Students of the Physical Sciences," by R. B. Lindsay, D. Van Nostrand Co., New York, 1950.

2 "Statistical Mechanics," by R. H. Fowler, Cambridge University Press, 1936.

3 "Statistical Thermodynamics," by R. H. Fowler and E. A. Guggenheim, Cambridge University Press, 1949.

[4] See, for instance, Ref. 3, p. 280.

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The Properties of Pure Liquids

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By a semiempirical approach, a method is found to calculate the specific heat of a normal pure liquid at constant pressure from the specific heat of the gaseous state at the same temperature. It is also found that the coefficient of thermal expansion, the compressibility, and the velocity of sound of the liquid can be calculated accurately if the density, the molecular weight, and the normal boiling temperature of the liquid at atmospheric pressure are known. Finally, a method of computing the thermal conductivity of all liquids, except liquid metals, from compressibility and density is developed. For normal liquids, the thermal conductivity can again be determined if only the normal boiling temperature, the density, and the molecular weight are known.

IN ROCKET and jet propulsion engineering, because of the necessity of considering a very wide range of possible fuels and propellants, one often meets the situation that the physical properties, such as heat capacity and thermal conductivity, of liquid of interest are not listed in the handbooks. Naturally the question to ask is whether such physical properties can be estimated from known simple quantities such as the boiling point, the molecular weight, and the density of the liquid. It is clear that such a correlation of liquid properties must come from the theory of the liquid state. Although there was no lack of work by physicists and physical chemists in this field, the agreement in the numerical values of theoretical prediction and of experimental observation is usually very poor. Therefore it may be justified to say that there are only very few useful results in the engineering sense. The difficulty here is evidently due to the rather indefinite structure of the liquid state in comparison to other states of matter: For the gaseous state, the interaction between the molecules can be almost neglected, and the predominating feature of the state is the translational and internal motions of the individual molecules. For the solid state, the reverse is true. The predominating feature is the interaction between the molecules or the atoms. For the liquid state of matter, the molecular interaction and the molecular motion are of equal importance. This fact leads to great complexities, and any theory of liquids, necessarily based upon a simplified model, is incomplete and is predicated upon many assumptions. The divergences between the theoretical predictions and the experimental observations are thus to be expected.

In this paper a somewhat new approach to the subject will be attempted. The theory will not be used to predict the physical properties from the molecular and the atomic characteristics, but rather used as a framework to fit the experimental data. In other words, the theory only gives the parameters that will enter into a relation, while the exact *form* of the functional relation is to be determined by the experimental data. Thus the approach here is that of "dimensional analysis" so successful in the older fields of engineering science, such as fluid mechanics and solid mechanics (1),[2] The two specific useful results of this investigation are a method to calculate the specific heats and a method to calculate the thermal conductivity of liquids. These methods are generally applicable to the so-called normal liquids, but a more general form for the thermal conductivity is available to include all liquids, normal or otherwise.

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[1] Robert H. Goddard Professor of Jet Propulsion.

[2] Numbers in parentheses refer to the References on page 24.

Lennard-Jones and Devonshire Theory of Liquids

One of the fairly successful theories of normal liquids is that given by Lennard-Jones and Devonshire (2). It is a theory of the "free volume" type in that the liquid molecule is assumed to move within a cage formed by the neighboring molecules. In this theory, the properties of the cage are determined by smoothing the bimolecular interactions of a face-centered cubic lattice where the nearest distance between molecules is a. The bimolecular interaction potential ϵ is taken from the theory of gaseous states and is expressed as

$$\epsilon(r) = \epsilon_m\left[\left(\frac{r^*}{r}\right)^{12} - 2\left(\frac{r^*}{r}\right)^{6}\right] \quad [1]$$

where r is the distance between the molecules, r^* the equilibrium distance, and ϵ_m is the magnitude of the potential at $r = r^*$.

The free energy F for an assembly of N molecules is found in this way to be

$$\frac{F}{N} = -kT\log\frac{(2\pi mkT)^{3/2}}{h^3} - kT\log j(T) - kT - \Lambda^*\left\{1.2\left(\frac{V^*}{V}\right)^2 - 0.5\left(\frac{V^*}{V}\right)^4\right\} - kT\log(2\pi\gamma g V) \quad [2]$$

In this equation, k is the Boltzmann constant, T the absolute temperature, $j(T)$ the internal partition function of the molecule. And furthermore

$$\Lambda^* = z\epsilon_m \quad [3]$$

where z is the coordination number and is 12 for face-centered cubic lattice, V is the volume per molecule, and V^* is the characteristic volume. They are related to a and r^* as follows

$$V = \frac{1}{\gamma}a^3,\quad V^* = \frac{1}{\gamma}r^{*3},\quad \gamma = \frac{1}{\sqrt{2}} \quad [4]$$

g is the following complicated integral

$$g = \int_0^{1/4} y^{1/2}\exp\left\{-\frac{\Lambda^*}{kT}\left(\frac{V^*}{V}\right)^4 l(y) + 2\frac{\Lambda^*}{kT}\left(\frac{V^*}{V}\right)^2 m(y)\right\} dy \quad [5]$$

where

$$l(y) = \frac{1 + 12y + 25.2y^2 + 12y^3 + y^4}{(1-y)^{10}} - 1,\ l(0) = 0 \quad [6]$$

$$m(y) = \frac{1+y}{(1-y)^4} - 1,\ m(0) = 0 \quad [7]$$

Once the free energy is calculated, the thermodynamic properties of the liquid can be obtained by simple differentiations. For instance, the energy per molecule E/N is

$$\frac{E}{N} = -T^2\frac{\partial}{\partial T}\left(\frac{F/N}{T}\right) \quad [8]$$

The pressure P is

$$P = -\frac{\partial}{\partial V}\left(\frac{F}{N}\right) \quad [9]$$

Mathematically then, the most difficult task of the theory is the evaluation of the integral g in Equation [5]. Recently, R. H. Wentorf, R. J. Buehler, J. O. Hirschfelder, and C. F. Curtiss (3) have carried out this tedious integration by numerical method, together with some inconsequential improvements in its formulation. Unfortunately, their extensive numerical tables are quite unsuitable for the present purpose of discovering the analytical functional relationships between the different quantities. However, for liquid states at low or atmospheric pressures, the ratio V/V^* is very nearly unity, while the ratio Λ^*/kT is of the order of 20. It is thus appropriate to seek the asymptotic expansion of the function g for large values of Λ^*/kT. This can be done as follows:

Let

$$s = \frac{\Lambda^*}{kT}\left(\frac{V^*}{V}\right)^4 \quad \ldots\ldots\ldots\ldots\ldots\ldots [10]$$

Then by expanding the functions $l(y)$ and $m(y)$ in power series of y, one has

$$-\frac{\Lambda^*}{kT}\left(\frac{V^*}{V}\right)^4 l(y) + 2\frac{\Lambda^*}{kT}\left(\frac{V^*}{V}\right)^2 m(y) = -s\cdot\eta =$$
$$-s\left[\left\{24 - 10\left(\frac{V}{V^*}\right)^2\right\}y + \left\{200.2 - 28\left(\frac{V}{V^*}\right)^2\right\}y^2 + \left\{1144 - 60\left(\frac{V}{V^*}\right)^2\right\}y^3 + \ldots.\right] \ldots [11]$$

η is thus the power series within the square bracket of Equation [11]. By inverting this power series, it is found that

$$y = a_1\eta + a_2\eta^2 + a_3\eta^3 + \ldots\ldots\ldots\ldots [12]$$

where

$$a_1 = \frac{1}{24 - 10\left(\frac{V}{V^*}\right)^2}$$

$$a_2 = -\frac{200.2 - 28\left(\frac{V}{V^*}\right)^2}{\left[24 - 10\left(\frac{V}{V^*}\right)^2\right]^3}$$

and

$$a_3 = \frac{2\left[200.2 - 28\left(\frac{V}{V^*}\right)^2\right]^2 - \left[1144 - 60\left(\frac{V}{V^*}\right)^2\right]\left[24 - 10\left(\frac{V}{V^*}\right)^2\right]}{\left[24 - 10\left(\frac{V}{V^*}\right)^2\right]^5} \quad \ldots\ldots\ldots [13]$$

At the lower limit of integration for g, $y = 0$, so $\eta = 0$. At the upper limit of integration, $y = 1/4$, so $\eta = l\ (1/4) - 2\ (V/V^*)^2\, m\ (1/4)$. $l\ (1/4)$ is, however, approximately 90, $m\ (1/4)$ is 2.95, and s is very large. Therefore it is correct to set the upper limit of integration in η as ∞. Then

$$g \sim a_1^{3/2}\int_0^\infty e^{-s\cdot\eta}\left[\eta^{1/2} + \frac{5}{2}\frac{a_2}{a_1}\eta^{3/2} + \frac{7}{2}\left\{\frac{a_3}{a_1} + \frac{1}{4}\left(\frac{a_2}{a_1}\right)^2\right\}\eta^{5/2} + \ldots.\right]d\eta = \frac{\sqrt{\pi}}{2}\left(\frac{a_1}{s}\right)^{3/2}\times$$
$$\left[1 + \frac{3\cdot5}{2\cdot2}\frac{a_2}{a_1}\frac{1}{s} + \frac{3\cdot5\cdot7}{2\cdot2\cdot2}\left\{\frac{a_3}{a_1} + \frac{1}{4}\left(\frac{a_2}{a_1}\right)^2\right\}\frac{1}{s^2} + \ldots.\right] \ldots\ldots [14]$$

By substituting the value of s from Equation [10], and the value of a's from Equation [13], the following expression for $\log g$ is obtained

$$\log g \sim \log\frac{\sqrt{\pi}}{2} + \frac{3}{2}\log\frac{kT\left(\frac{V}{V^*}\right)^4}{\Lambda^*\left[24 - 10\left(\frac{V}{V^*}\right)^2\right]} - \frac{3\cdot5}{2\cdot2}\left(\frac{V}{V^*}\right)^8\frac{kT}{\Lambda^*}\frac{200.2 - 28\left(\frac{V}{V^*}\right)^2}{\left[24 - 10\left(\frac{V}{V^*}\right)^2\right]} + \frac{3\cdot5\cdot7}{2\cdot2\cdot2}\left(\frac{V}{V^*}\right)^8\left(\frac{kT}{\Lambda^*}\right)^2\times$$
$$\frac{12\left[200.2 - 28\left(\frac{V}{V^*}\right)^2\right]^2 - 7\left[1144 - 60\left(\frac{V}{V^*}\right)^2\right]\left[24 - 10\left(\frac{V}{V^*}\right)^2\right]}{7\left[24 - 10\left(\frac{V}{V^*}\right)^2\right]^4} \quad \ldots [15]$$

It is evident that the expansion of Equation [15] is the appropriate one for large values of Λ^*/kT. By combining Equation [15] with Equation [2], the free energy of the liquid state can be obtained. Differentiation according to Equations [8] and [9] then gives the other thermodynamic quantities.

Specific Heat at Constant Volume

If $\frac{E^{int}}{N}$ is the internal energy per molecule, i.e.,

$$\frac{E^{int}}{N} = kT^2\frac{\partial}{\partial T}\{\log j(T)\} \quad \ldots\ldots\ldots\ldots [16]$$

then Equation [8] gives

$$\frac{E}{N} = \frac{E^{int}}{N} + 3kT - \Lambda^*\left\{1{\cdot}2\left(\frac{V^*}{V}\right)^2 - 0.5\left(\frac{V^*}{V}\right)^4\right\} - \frac{3\cdot5}{2\cdot2}\frac{200.2 - 28\left(\frac{V}{V^*}\right)^2}{\left\{24 - 10\left(\frac{V}{V^*}\right)^2\right\}^2}\left(\frac{V}{V^*}\right)^4\frac{kT}{\Lambda^*}kT \ldots [17]$$

where terms of third power in T and higher are dropped. By differentiating Equation [17] once more with respect to T, the specific heat at constant volume can be determined. Let C_v^l be the molar specific heat of the liquid state at constant volume, and C^{int} be the molar specific heat of the internal energy alone, i.e., by taking N to be Avogadro's number

$$C^{int} = \frac{\partial}{\partial T}E^{int} \quad \ldots\ldots\ldots\ldots [18]$$

Then

$$C_v^l = C^{int} + 3R - \frac{3\cdot5}{2\cdot2}\frac{200.2 - 28\left(\frac{V}{V^*}\right)^2}{\left\{24 - 10\left(\frac{V}{V^*}\right)^2\right\}^2}\left(\frac{V}{V^*}\right)^4\frac{kT}{\Lambda^*}R \ldots [19]$$

where R is the universal gas constant or $R = Nk$.

Equation [19] demonstrates the gratifying result that aside from the small correction of the third term, the specific heats at constant volume for the liquid state and the solid state are the same. This is in agreement with the concept that for pressures and temperatures below the critical pressure and the critical temperature, there are more points of similarity between the liquid state and the solid state than there are between the liquid state and the gaseous state. The full classical value of $3R$ means the absence of quantal effects. This is of course generally true, as will be discussed in more detail in the appendix.

The molar specific heat at constant pressure C_p^g for the gaseous state can be calculated as

$$C_p^g = C^{int} + \frac{5}{2}R \quad \ldots\ldots\ldots\ldots [20]$$

For molecules that are not excessively elongated as to restrict their rotational freedom in the liquid state, the molecular energy of the internal degrees of freedom must be the same in the liquid state as in the gaseous state. Therefore the values of C^{int} in Equations [19] and [20] must be the same. Then Equation [19] can be also written as

$$C_v^l = C_p^g + R\left[0.5 - \frac{15}{2}\frac{200.2 - 28\left(\frac{V}{V^*}\right)^2}{\left\{24 - 10\left(\frac{V}{V^*}\right)^2\right\}^2}\left(\frac{V}{V^*}\right)^4\frac{kT}{\Lambda^*}\right] \ldots [21]$$

Now since the third term to the right of Equation [21] is a small correction term, it would be all right to use the following approximations, true for liquid state at low or atmospheric pressures, i.e., at pressures much lower than the critical pressure. Furthermore

$$\left.\begin{aligned} V/V^* &\sim 1 \\ \frac{kT_b}{\Lambda^*} &\sim 16.5 \end{aligned}\right\} \quad \ldots\ldots [22]$$

where T_b is the normal boiling temperature of the liquid at atmospheric pressure. Then Equation [21] becomes

$$C_v^l = C_p^g + R\left[0.5 - 0.4\,\frac{T}{T_b}\right] \quad \ldots\ldots [23]$$

Therefore the specific heat of liquids at constant volume can be easily calculated once the specific heat of the gaseous state and the boiling point are known.

Thermal Expansion and Compressibility

The equation of state for the liquid can be determined by using Equation [9]. By using only two terms of the expansion for q as given by Equation [15], one has

$$P = \frac{\Lambda^*}{V}\left\{2\left(\frac{V^*}{V}\right)^4 - 2.4\left(\frac{V^*}{V}\right)^2\right\} + \frac{kT}{V}\,\frac{84 - 20\left(\frac{V}{V^*}\right)^2}{12 - 5\left(\frac{V}{V^*}\right)^2} \quad \ldots [24]$$

Now the coefficient of thermal expansion α is defined as

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P \quad \ldots\ldots [25]$$

Then by differentiating Equation [24] with respect to T, keeping the pressure P constant, one has

$$\alpha\left[\frac{\Lambda^*}{V}\left\{10\left(\frac{V^*}{V}\right)^4 - 7.2\left(\frac{V^*}{V}\right)^2\right\} + \frac{kT}{V}\left(\frac{84 - 20\left(\frac{V}{V^*}\right)^2}{12 - 5\left(\frac{V}{V^*}\right)^2} - \frac{360\left(\frac{V}{V^*}\right)^2}{\left[12 - 5\left(\frac{V}{V^*}\right)^2\right]^2}\right)\right] = \frac{k}{V}\,\frac{84 - 20\left(\frac{V}{V^*}\right)^2}{12 - 5\left(\frac{V}{V^*}\right)^2}$$

However, the pressure P is very small in comparison with the size of both terms in the right of Equation [24], i.e.,

$$\frac{\Lambda^*}{V}\left\{2\left(\frac{V^*}{V}\right)^4 - 2.4\left(\frac{V^*}{V}\right)^2\right\} + \frac{kT}{V}\,\frac{84 - 20\left(\frac{V}{V^*}\right)^2}{12 - 5\left(\frac{V}{V^*}\right)^2} \cong 0$$

Therefore the equation for the thermal expansion can be simplified to

$$\alpha\left[\Lambda^*\left\{8\left(\frac{V^*}{V}\right)^4 - 4.8\left(\frac{V^*}{V}\right)^2\right\} - kT\,\frac{360\left(\frac{V}{V^*}\right)^2}{\left\{12 - 5\left(\frac{V}{V^*}\right)^2\right\}^2}\right] = k\,\frac{84 - 20\left(\frac{V}{V^*}\right)^2}{12 - 5\left(\frac{V}{V^*}\right)^2}$$

By again using the approximations of Equation [22], one has finally

$$\alpha T_b = \frac{0.554}{3.2 - 0.445\,\frac{T}{T_b}} \quad \ldots\ldots [26]$$

The compressibility β of the liquid is defined as

$$\beta = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T \quad \ldots\ldots [27]$$

By following a similar procedure as outlined in the preceding paragraph for α, the compressibility is found to be

$$\beta\,\frac{RT_b}{V_l} = \frac{1}{52.8 - 7.35\left(\frac{T}{T_b}\right)} \quad \ldots\ldots [28]$$

where R is again the universal gas constant, V_l is the volume per mole of the liquid.

Equations [26] and [28] give the coefficient of thermal expansion α and the compressibility β according to the Lennard-Jones and Devonshire theory of liquids. Other theories of liquids give different formulas. For instance, the free volume theory of H. Eyring and J. O. Hirschfelder (4) gives

$$\alpha T_b = \frac{3}{9.4 - 4\left(\frac{T}{T_b}\right)} \quad \ldots\ldots [29]$$

and

$$\beta\,\frac{RT_b}{V_l} = \frac{1}{3.13\left(9.4\,\frac{T_b}{T} - 4\right)} \quad \ldots\ldots [30]$$

Such discrepancies between the theories probably indicate

TABLE 1 COEFFICIENT OF THERMAL EXPANSION OF LIQUIDS

Liquid	Formula	T_b, °K	T, °K	$\alpha \times 10^3$, °K^{-1}	T/T_b	αT_b
Acetone	$(CH_3)_2CO$	329.7	293.2	1.071	0.890	0.353
Aniline	$C_6H_5NH_2$	457.6	293.2	0.855	0.641	0.382
Arsenic trichloride	$AsCl_3$	403.4	293.2	1.029	0.728	0.415
Benzene	C_6H_6	353.2	293.2	1.237	0.830	0.437
Bromine	Br_2	332.0	293.2	1.132	0.883	0.376
Carbon disulfide	CS_2	319.5	293.2	1.218	0.918	0.390
Carbon tetrachloride	CCl_4	350.0	293.2	1.236	0.838	0.433
Chloroform	$CHCl_3$	334.5	293.2	1.273	0.877	0.426
Ethyl ether	$(C_2H_5)_2O$	307.8	293.2	1.656	0.953	0.510
Ethyl iodide	C_2H_5I	345.4	293.2	1.179	0.848	0.407
Trimethyl ethane	C_5H_{12}	301.2	293.2	1.598	0.973	0.481
Phosphorus tribromide	PBr_3	446.1	293.2	0.868	0.657	0.387
Phosphorus trichloride	PCl_3	348.7	293.2	1.154	0.841	0.402
	....	....	....	1.211	....	0.422
Phosphorus oxychloride	$POCl_3$	378.5	293.2	1.116	0.775	0.423
Pentane	C_5H_{12}	309.4	293.2	1.608	0.948	0.498
i-Propyl chloride	C_3H_7Cl	308.6	293.2	1.591	0.950	0.491
Isoprene	C_5H_8	307.2	293.2	1.567	0.955	0.481
Silicon bromide	$SiBr_4$	426.2	293.2	0.983	0.688	0.419
Silicon chloride	$SiCl_4$	330.8	293.2	1.430	0.886	0.473
Stannic chloride	$SnCl_4$	387.3	293.2	1.178	0.757	0.456
Titanium tetrachloride	$TiCl_4$	409.6	293.2	0.998	0.715	0.409
o-Toluidine	$C_7H_7NH_2$	473.0	293.2	0.847	0.620	0.401

that neither theory is really accurate enough for calculations of α and β. But both theories give αT_b and $\beta RT_b/V_l$ as functions of the temperature ratio T/T_b. Therefore it seems justified to consider such functions as unknown theoretically, but to be determined by experimental data. Once determined, these functions are then universal and applicable to all normal liquids.

Table 1 lists the values of the coefficient of thermal expansion at 20C° taken from the Landolt-Börnstein Tabellen for various normal liquids at atmospheric pressure. The nondimensional quantity αT_b is then plotted against T/T_b in Fig. 1, where the relations specified by Equations [26] and [29] are also plotted. Although the theories do predict the increasing thermal expansion with temperature, a behavior contrary to that of the gaseous state, the experimental data lie between the theoretical curves and are grouped definitely around a different curve. This empirical curve is drawn as a heavy line in Fig. 1. Therefore the surmise that αT_b is a function of T/T_b is now justified. By using this empirical curve, the thermal expansion of normal liquids can be calculated to 10 per cent accuracy once the boiling point T_b is known.

Table 2 lists the values of the compressibility of normal liquids at approximately atmospheric pressure taken again from the Landolt-Börnstein Tabellen. The nondimensional quantity $\beta RT_b/V_l$ is then plotted against the temperature ratio T/T_b in Fig. 2. The theoretical curves specified by Equations [28] and [30] are also plotted. It is seen that a similar situation as for α exists. In fact, the empirical curve can be very closely represented by

$$\beta \frac{RT_b}{V_l} = \frac{1}{101.6 - 82.4\left(\frac{T}{T_b}\right)} \quad \ldots\ldots [31]$$

Therefore the compressibility of any normal liquid can be calculated with 10 per cent accuracy if the boiling point T_b, the liquid density, and the molecular weight are known.

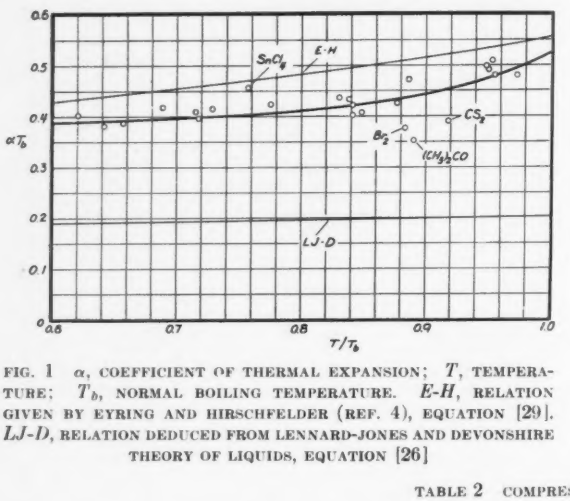

FIG. 1 α, COEFFICIENT OF THERMAL EXPANSION; T, TEMPERATURE; T_b, NORMAL BOILING TEMPERATURE. *E-H*, RELATION GIVEN BY EYRING AND HIRSCHFELDER (REF. 4), EQUATION [29]. *LJ-D*, RELATION DEDUCED FROM LENNARD-JONES AND DEVONSHIRE THEORY OF LIQUIDS, EQUATION [26]

Specific Heat at Constant Pressure

For many engineering calculations, what is desired is not the specific heat at constant volume C_v^l but rather the specific heat at constant pressure C_p^l. According to the general thermodynamic laws, the difference between C_p^l and C_v^l is given by

$$C_p^l - C_v^l = \frac{\alpha^2}{\beta} V_l T \quad \ldots\ldots [32]$$

where α and β are the thermal expansion and compressibility, respectively. By combining Equations [23] and [32], the molar specific heat at constant pressure for the liquid state is related to the molar specific heat at constant pressure for the gaseous state as follows

$$C_p^l - C_p^g = R\left\{0.5 - 0.4\frac{T}{T_b} + \frac{(\alpha T_b)^2}{\left(\beta \frac{RT_b}{V_l}\right)} \frac{T}{T_b}\right\} \quad \ldots\ldots [33]$$

The relation given by Equation [33] can be compared with

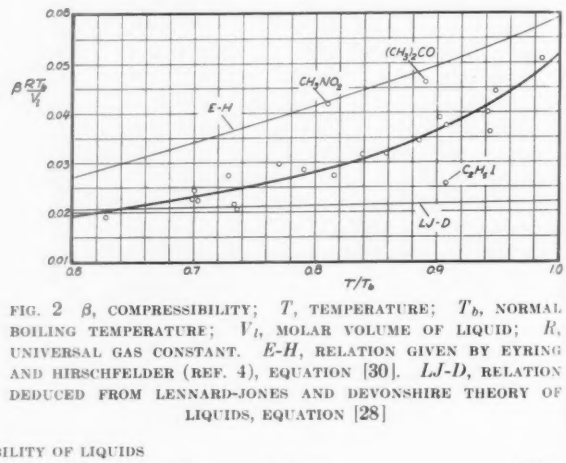

FIG. 2 β, COMPRESSIBILITY; T, TEMPERATURE; T_b, NORMAL BOILING TEMPERATURE; V_l, MOLAR VOLUME OF LIQUID; R, UNIVERSAL GAS CONSTANT. *E-H*, RELATION GIVEN BY EYRING AND HIRSCHFELDER (REF. 4), EQUATION [30]. *LJ-D*, RELATION DEDUCED FROM LENNARD-JONES AND DEVONSHIRE THEORY OF LIQUIDS, EQUATION [28]

TABLE 2 COMPRESSIBILITY OF LIQUIDS

Liquid	Formula	Molecular weight	T_b, °K	T, °K	Density, gr/cc	$\beta \times 10^6$, atm^{-1}	T/T_b	$\frac{\beta RT_b}{V_l}$
Acetone	$(CH_3)_2CO$	58.08	329.7	293.2	0.792	125.6	0.890	0.0464
Benzene	C_6H_6	78.11	353.3	303.2	0.868	98.5	0.858	0.0318
	....	...	...	333.2	0.836	116.4	0.944	0.0362
Carbon disulfide	CS_2	76.13	319.7	303.2	1.261	102.0	0.948	0.0444
Carbon tetrachloride	CCl_4	153.84	350.0	293.2	1.595	105.8	0.838	0.0316
Chlorobenzene	C_6H_5Cl	112.56	405.2	283.2	1.107	72	0.698	0.0226
Chloroform	$CHCl_3$	119.39	334.5	303.2	1.49	109.5	0.907	0.0375
Ethyl ether	$(C_2H_5)_2O$	74.12	307.8	303.2	0.713	210	0.986	0.0510
Ethyl bromide	C_2H_5Br	108.98	311.2	293.2	1.430	120	0.942	0.0402
Ethyl iodide	C_2H_5I	155.98	345.4	313.2	1.91	74	0.907	0.0257
n-Heptane	C_7H_{16}	100.20	371.7	303.2	0.684	134	0.815	0.0274
n-Hexane	C_6H_{14}	86.17	342.2	303.2	0.66	159	0.885	0.0343
Nitrobenzene	$C_6H_5NO_2$	123.11	484.1	303.2	1.1987	49	0.627	0.0190
Nitromethane	CH_3NO_2	61.04	374.2	303.2	1.13	73.6	0.810	0.0419
n-Octane	C_8H_{18}	114.23	399.0	293.2	0.704	101.6	0.735	0.0205
Paraldehyde	$C_6H_{12}O_3$	132.16	397.6	291.2	0.994	88.2	0.733	0.0216
Silicon bromide	$SiBr_4$	347.72	426.2	298.2	2.814	86.6	0.700	0.0245
Silicon chloride	$SiCl_4$	169.89	330.8	298.2	1.483	165.2	0.902	0.0391
Titanium tetrachloride	$TiCl_4$	189.73	409.6	298.2	1.726	89.8	0.728	0.0275
Stannic chloride	$SnCl_4$	260.53	387.3	298.2	2.232	108.9	0.770	0.0296
Toluene	$C_6H_5CH_3$	92.13	384.0	303.2	0.862	96.5	0.790	0.0285
o-Xylene	$C_6H_4(CH_3)_2$	106.16	417.2	293.2	0.875	79.7	0.703	0.0224

the equation given by S. W. Benson (5) for the difference of molar specific heats at constant pressure for the saturated liquid and saturated vapor. Benson's relation is

$$C_p^l - C_p^g = n\Delta E_{vap}\,\alpha + R$$

where n is approximately 5/3 for a large number of substances, ΔE_{vap} is the molar energy of evaporation, and α the thermal expansion coefficient defined by Equation [25]. However, this relation, which requires a knowledge of n and ΔE_{vap}, seems to be less convenient to use than Equation [33] together with the semi-empirical information on the thermal expansion α and the compressibility β.

With the empirically determined relations for the coefficient of thermal expansion α and the compressibility β, the right side of Equation [33] can be calculated as a function of the temperature ratio T/T_b. This is carried out in Table 3. It

TABLE 3 DIFFERENCE OF SPECIFIC HEATS OF LIQUID AND GAS

T/T_b	αT_b	$\beta \frac{RT_b}{V_l}$	$\frac{(\alpha T_b)^2}{\left(\beta \frac{RT_b}{V_l}\right)} \frac{T}{T_b}$	0.5–0.4 $\frac{T}{T_b}$	$\frac{C_p^l - C_p^g}{R}$
0.6	0.392	0.0192	4.80	0.26	5.06
0.7	0.398	0.0232	4.78	0.22	5.00
0.8	0.410	0.0280	4.80	0.18	4.98
0.9	0.445	0.0365	4.88	0.14	5.02
1.0	0.525	0.0520	5.30	0.10	5.40

is seen that except possibly near the boiling point, the difference between the molar specific heats of liquid and gas at constant pressure is very nearly $5R$, or

$$C_p^l - C_p^g = 10 \text{ cal/°C mole} \quad \ldots\ldots [34]$$

This is indeed a remarkably simple result.

The comparison of the calculated specific heat of liquid using Equation [34] with the experimental data is exhibited in Table 4. Since the theory is developed for normal liquids, molecules containing hydroxyl group or amino group, and molecules that are excessively elongated should be excluded. The experimental data are taken also from the Landolt-Börnstein Tabellen. For diatomic molecules, the theoretical value of C_p^g without vibrational heat is used. This value of 7 cal/°C is correct for the prevailing low temperature. For silver chloride, this value of C_p^g may be too low. The first half of the table shows excellent agreement between the calculated and the experimental molar specific heat of liquid at constant pressure, with differences well within the experimental error. The only exception is carbon disulfide. This success of the theory is notable for the very wide range of temperature covered, from 120° K for nitric oxide to 763°K for silver chloride.

The second half of Table 4 indicates, however, considerable discrepancy between the calculated specific heat and the experimental specific heat. The calculated values are too large by approximately 4 cal/°C. A similar discrepancy for Trouton's ratio, the ratio of heat of evaporation and the boiling temperature T_b, also occurs for this group of liquids (6). Such differences are well outside the probable experimental error. Furthermore, the temperatures concerned, although low, are not low enough for the occurrence of quantal effects (see appendix). Nor is there any likelihood of a different molecular interaction than the first group of liquids in the table. This is shown by their similar transport properties in the gaseous state. The only possible explanation seems to be the association effects. For instance, oxygen tends to associate to O_4 molecule in liquid state. If so, the molar specific heat of the liquid will be twice as large as listed in the table, or 25 cal/°C. The fictitious O_4 molecule in gaseous state then should have a C_p^g of 15 cal/°C. This is an entirely reasonable value.

From the foregoing discussion, it seems justified to use Equation [34] for normal liquids at room temperature or higher when association and dissociation are absent. For normal liquids, the accuracy of present method is very much higher than the method, suggested by R. R. Wenner (7), based upon counting individual atoms in the liquid molecule. Of course it may be argued that when it is necessary to predict the specific heat of liquid, the specific heat for the gaseous state is generally also not available, and then Equation [34] is of no practical utility. Fortunately, however, it is not necessary to depend on direct experimental determination of the specific heat of gaseous state. C_p^g can be very accurately calculated from the fundamental frequencies of the molecule determined by spectroscopy. Or C_p^g can be calculated with sufficient accuracy from the averaged frequencies for each type of chemical bonds, a method recently rendered more complete by R. V. Meghreblian (8). As an example of such a situation, one may consider the molecule $CHCl_2Br$, bromodichloromethane. This molecule is not even listed in the well-known Handbook of Chemistry and Physics. But Meghreblian has calculated its molar specific heat C_p^g at 27°C to be 16.2 cal/°C. Then according to Equation [34], the molar specific heat of the liquid C_p^l at the same temperature is 26.2 cal/°C. Since the molecular weight of this compound is 163.85, the specific

TABLE 4 SPECIFIC HEAT OF LIQUIDS AT CONSTANT PRESSURE

Liquid	Formula	Molecular weight	T_b, °K	T, °K	C_p^g, cal/°C, exp	C_p^l, cal/°C, calc'd	C_p^l, cal/°C, exp
Ammonia	NH_3	17.032	239.8	213.2	8.0	18.0	17.9
....	.....	.....	....	273.2	8.7	18.7	18.7
Acetone	$(CH_3)_2CO$	58.08	329.7	313.2	20.1	30.1	30.8
Benzene	C_6H_6	78.11	353.3	293.2	21.8	31.8	32.5
....	.....	.....	.....	323.2	23.3	33.3	34.3
Bromine	Br_2	159.83	332.0	270.0	7.0[a]	17.0	17.1
Carbon disulfide	CS_2	76.13	319.7	290.7	12.0	22.0	18.4
Carbon tetrachloride	CCl_4	153.84	350.0	273.2	21.5	31.5	30.9
....	.....	.....	.....	293.2	20.7	30.7	31.8
Chloroform	$CHCl_3$	119.39	334.5	313.2	17.2	27.2	27.9
Ethyl ether	$(C_2H_5)_2O$	74.12	307.8	303.2	31	41	40.5
Nitric oxide	NO	30.01	121.4	120	7.0[a]	17.0	17.3
Silver chloride	AgCl	143.34	1823	763	<7.0, >9.0	<17.0, >19.0	18.5
Stannic chloride	$SnCl_4$	260.53	387.3	287–371	24.4	34.4	38.5
Sulphur dioxide	SO_2	64.06	263.2	273.2	9.9	19.9	20.4
Argon	A	39.944	87.4	85.0	5.0	15.0	10.5
Carbon monoxide	CO	28.01	81.1	69.4	7.0[a]	17.0	14.27
Methane	CH_4	16.04	111.7	100	8.0	18.0	13.01
Nitrogen	N_2	28.016	77.3	64.7	7.0[a]	17.0	13.15
....	.....	.....	....	72.8	7.0[a]	17.0	13.33
Oxygen	O_2	32.00	90.1	73.2	7.0[a]	17.0	12.60

[a] Theoretical value for diatomic molecules without vibrational heat.

heat at constant pressure of the liquid is 0.1598 cal/gr °C, or 0.1598 Btu/lb °F.

Liquid Metals

Pure metal atoms do not associate into molecules. Therefore the specific heat of pure liquid metals should be correlated on the basis of one gram atomic weight. When this is done, pure liquid metals give a specific heat at constant pressure from 6.4 cal/°C to 8 cal/°C. Therefore it is reasonable to take as a first approximation

$$C_p^l = 7 \text{ cal/°C} \quad \ldots\ldots\ldots\ldots\ldots\ldots [35]$$

per gram atomic weight. Since the specific heat at constant volume should be close to $3R$ or 6 cal/°C, Equation [35] shows that the difference between C_p and C_v for liquid metals is only 1 cal/°C. This is very much less than the corresponding value found for normal liquids as discussed in the previous section. For the particular case of liquid mercury, a more detailed discussion has been given by J. F. Kincaid and H. Eyring (9). They have also pointed out that the difference in behavior of the liquid metals from that of normal liquids is due to the difference in the interaction potential of the constituent particles. Since the interaction in normal liquids is the interaction between molecules, the interaction in liquid metals is the interaction between the metallic atoms. This difference is certainly expected.

Velocity of Sound

The velocity of propagation of small disturbances is generally called the velocity of sound c and is a very important quantity in fluid dynamics. The general formula for computing this quantity is

$$c^2 = -\frac{v^2\,dP}{dv} = -\frac{1}{\rho}\left(\frac{V\,dP}{dV}\right) \quad \ldots\ldots\ldots\ldots [36]$$

where v is the volume for unit mass of the liquid, ρ is the density or $1/v$, and the derivative is to be computed according to the adiabatic process.

If the frequency of the sound wave is sufficiently low, or if the characteristic time of the small disturbance is longer than the relaxation time for reaching thermodynamic equilibrium, then it can be easily shown that

$$c^2 = \frac{1}{\rho\beta}\frac{C_p^l}{C_v^l} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [37]$$

where β is the compressibility defined by Equation [27]. For normal liquids, β is given by Equation [31], and according to Table 3, the difference between C_p and C_v is approximately 9.6 cal/°C. Let M be the molecular weight. Then

$$c^2 = \frac{RT_b}{M}\left(101.6 - 82.4\,\frac{T}{T_b}\right)\frac{C_p^l}{C_p^l - 9.6} \quad \ldots\ldots\ldots [38]$$

The comparison between the calculated and the experimental values of the velocity of sound is shown in Table 5. It is seen that with the exception of carbon disulfide, Equation [38] predicts the velocity of sound to within one per cent of the experimental value. This accuracy is perhaps expected, since Equation [38] already contains the empirically deduced relations for $C_p - C_v$ and β. Nevertheless, the agreement is satisfying in that it indicates the inner consistency of the theory. The case of CS_2 may be partially explained by the exceptionally low experimental value of C_p. Table 4 shows that the theoretical value for C_p^l of carbon disulfide is considerably higher. If so, the calculated velocity of sound for CS_2 will be lowered and the agreement with the experimental data will be better. Therefore it is justified to say that Equation [38] gives a satisfactory prediction of the velocity of sound for pure normal liquids. Since C_p^l increases with temperature, Equation [38] shows that the velocity of sound decreases with temperature. This behavior of normal liquid is contrary to that of gaseous state, for which the velocity of sound increases with temperature.

Transport Properties

The properties of liquids discussed in the preceding sections are all properties at thermodynamic equilibrium. Transport properties are properties of matter not at equilibrium, and the theory of transport properties is very much more complex than the theory of equilibrium properties. A "basic" approach to the theory of transport properties of liquids was made by J. G. Kirkwood and by M. Born and H. S. Green. However, no useful result has yet been obtained by their theories. Here the method of simple model followed by fitting the theoretical relation to empirical data will be used. An example of this method applied to the transport properties of liquids is Eyring's theory of viscosity of liquids (10).

According to Eyring's theory, the viscosity μ of a liquid at temperature T is related to the energy of vaporization ΔE_{vap} per mole of the liquid as follows.

$$\mu = \frac{hN}{V_l}\exp\left(\Delta E_{vap}/2.45RT\right) \quad \ldots\ldots\ldots\ldots [39]$$

where h is Planck's constant, N Avogadro's number, and V_l the molar volume of the liquid. For normal liquids, energy of vaporization is related to the normal boiling temperature T_b by Trouton's rule. That is

$$\Delta E_{vap} \cong 9.4RT_b \quad \ldots\ldots\ldots\ldots\ldots\ldots [40]$$

By combining Equations [39] and [40], the viscosity in centipoises is given by

$$\mu \cong \frac{0.3990}{V_l}\exp\left(3.83T_b/T\right) \quad \ldots\ldots\ldots\ldots [41]$$

where V_l is in cc per mole.

Thermal Conductivity

The elementary theory of heat conduction in gas gives (11) the thermal conductivity λ of a gas as

$$\lambda = \frac{1}{3}\,clc_v \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots [42]$$

where c is the velocity of sound, c_v the specific heat of the gas at constant volume per unit volume, and l is the mean free path of the molecules in the gas. In other words, l is the mean distance for which the molecules will maintain their individual velocities. I. Estermann and J. E. Zimmerman (12) noted that if l is interpreted as the distance, a lattice wave in a solid will travel before scattering, then the thermal conductivity of solid due to lattice oscillations calculated by R. E. B. Makinson (13) can be easily obtained from the relation of Equation [42]. This observation clearly shows the fundamental character of Equation [42]. It should then be true

TABLE 5 VELOCITY OF SOUND

Liquid	Formula	Molecular weight	T_b, °K	T, °K	C_p^l, cal/°C	$c_{calc} \times 10^{-5}$, cm/sec	c_{exp}[a] $\times 10^{-5}$, cm/sec
Benzene	C_6H_6	78.11	353.3	290.2	39.8	1.176	1.166
Carbon disulfide	CS_2	76.13	319.7	288.2	18.2	1.350	1.161
Chloroform	$CHCl_3$	119.39	334.5	288.2	27.9	0.967	0.983
Ethyl ether	$(C_2H_5)_2O$	74.12	307.8	288.2	39.8	1.022	1.032

[a] Taken from Smithsonian tables.

for all three states of matter, if the different quantities entering into it are properly identified. P. W. Bridgman (4), in fact, suggested such a correlation as early as 1931. However, the following theory differs from that of Bridgman in important details, as will be explained presently.

For liquids other than liquid metals, the heat must be conducted as oscillations of the molecules from its mean position, similar to the heat conduction in solid by "lattice waves." Therefore if Equation [42] will be used to calculate the thermal conductivity of a liquid, the c is the velocity of sound in the liquid. This is exactly what Bridgman proposed. It will not be correct, however, to compute c by Equation [37], because the frequencies of the lattice waves are generally so high as to not allow the thermodynamic equilibrium assumed for Equation [37]. Therefore there are some questions in determining c. For lack of better information, let c be tentatively taken simply as

$$c \sim 1/\sqrt{\rho\beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots [43]$$

Thus the uncertain ratio of specific heats in Equation [37] is dropped.

The appropriate mean free path l for the lattice waves in liquid must be the size of the local organization of the liquid molecules. This size of local organization is a few times the molecular spacing a. Therefore according to Equation [4]

$$l \sim V^{1/3} \quad \ldots\ldots\ldots\ldots\ldots\ldots [44]$$

where V is the liquid volume per molecule. l is thus of the order of a few ångströms.

Bridgman proposed to identify c_v as the total heat capacity including the internal degrees of freedom. However, with l only of the order of 10^{-7} cm, and with c as large as 10^5 cm per sec, the characteristic time for the lattice waves must be of the order of 10^{-12} sec. This is much shorter than the known relaxation time for the internal degrees of freedom of molecules. Then it is reasonable to suppose that the internal degrees of freedom of the molecule do not participate in the conduction of heat. Therefore for computing the thermal conductivity of liquids, the specific heat should be that of external degrees of freedom of the molecules only. The specific heat per mole is then approximately $3R$. Or

$$c_v \sim \frac{3R}{V_l} \quad \ldots\ldots\ldots\ldots\ldots\ldots [45]$$

By combining Equations [43], [44], and [45], the thermal conduction of liquid can be written as

$$\lambda \sim \frac{1}{\sqrt{\rho\beta}} V^{1/3} \frac{3R}{V_l}$$

The factor of proportionality of the above relation remains undetermined. To determine it, one has to introduce the experimental data. This is done in Table 6 and Fig. 3. The compressibility data were taken from the Landolt-Börnstein Tabellen and the thermal conductivity from the Appendix of McAdam's book on heat transfer (15). These data include such "abnormal" liquids as water and alcohols. It thus seems that the great majority of experimental thermal conductivity falls within 20 per cent of the calculated value if one simply takes

$$\lambda = \frac{1}{\sqrt{\rho\beta}} V^{1/3} \frac{3R}{V_l} = \frac{1}{\sqrt{\rho\beta}} \left(\frac{M}{N\rho}\right)^{1/3} \frac{3R\rho}{M} \quad \ldots\ldots [46]$$

Therefore the factor of proportionality is just unity. By comparing Equations [42] and [44], it is seen that mean free path l of the lattice waves is approximately 3 times the intermolecular distance. The local structure of the liquid may be pictured as a cubic lattice having nearly 12 neighbors to the central molecule. This deduction is entirely in agreement with the adopted concept of the liquid state. Equation [46] shows that the thermal conductivity of all liquids, normal or otherwise, can be calculated satisfactorily if the molecular weight, the density, and the compressibility of the liquid are known.

TABLE 6 THERMAL CONDUCTIVITY

Liquid	Formula	Molecular weight	Temperature, °C	Density, gr/cc	$\beta \times 10^{-5}$, atm^{-1}	$(\rho\beta)^{-1/2} \times 10^{-5}$, cm/sec	$V^{1/3} \times 10^8$, cm	$\frac{V^{1/3}}{\sqrt{\rho\beta}} \frac{3R}{V_l}$	λ_{exp}, cal/cm °C sec	$\frac{\lambda_{exp}}{\frac{V^{1/3}}{\sqrt{\rho\beta}} \frac{3R}{V_l}}$
Acetic acid	CH_3COOH	60.05	20	1.049	90.6	1.033	4.56	0.000491	0.000409	0.833
Acetone	$(CH_3)_2CO$	58.08	20	0.792	125.6	1.010	4.96	0.000407	0.000430	1.056
Allyl alcohol	$C_2H_3CH_2OH$	58.08	20–30	0.855	75	1.257	4.83	0.000533	0.000430	0.807
Amyl alcohol	$C_5H_{11}OH$	88.15	17.7	0.814	90.5	1.172	5.65	0.000365	0.000392	1.075
Aniline	$C_6H_5NH_2$	93.12	20	1.022	36.1	1.657	5.32	0.000577	0.000413	0.715
Benzene	C_6H_6	78.11	30	0.868	98.5	1.089	5.30	0.000382	0.000380	0.995
	....	....	60	0.836	116.4	1.020	5.37	0.000350	0.000359	1.026
Carbon dioxide	CO_2	44.01	13.3[a]	0.960	624.4	0.412	4.23	0.000246	0.000245	0.995
Carbon disulfide	CS_2	76.13	30	1.261	102.0	0.888	4.64	0.000407	0.000384	0.945
Carbon tetrachloride	CCl_4	153.84	20	1.595	105.8	0.775	5.43	0.000260	0.000392	1.510
Chlorobenzene	C_6H_5Cl	112.56	10	1.107	72	1.128	5.53	0.000336	0.000343	1.020
Chloroform	$CHCl_3$	119.39	30	1.49	109.5	0.788	5.11	0.000299	0.000330	1.104
Ethyl alcohol	C_2H_5OH	46.07	20	0.789	112	1.071	4.59	0.000502	0.000434	0.865
Ethyl bromide	C_2H_5Br	108.98	20	1.430	120	0.769	5.01	0.000301	0.000289	0.962
Ethyl ether	$(C_2H_5)_2O$	74.12	30	0.713	210	0.808	5.56	0.000258	0.000330	1.280
Ethyl iodide	C_2H_5I	155.98	40	1.91	74	0.847	5.15	0.000318	0.000264	0.830
Ethylene glycol	$(CH_2OH)_2$	62.07	0	1.12	34	1.63	4.51	0.000790	0.000632	0.800
Glycerine	$(CH_2OH)_2$-CHOH	92.09	20	1.260	22	1.912	4.94	0.000773	0.000678	0.877
n-Heptane	C_7H_{16}	100.20	30	0.684	134	1.051	6.25	0.000268	0.000334	1.246
n-Hexane	C_6H_{14}	86.17	30	0.66	159	0.983	6.01	0.000270	0.000330	1.220
Hexyl alcohol	$C_6H_{12}OH$	102.17	30	0.818	60	1.437	5.91	0.000405	0.000384	0.948
Methyl alcohol	CH_3OH	32.04	20	0.7928	123.5	1.016	4.07	0.000609	0.000512	0.841
Nitrobenzene	$C_6H_5NO_2$	123.11	30	1.199	49	1.313	5.54	0.000422	0.000393	0.930
Nitromethane	CH_3NO_2	61.04	30	1.13	73.6	1.104	4.47	0.000544	0.000517	0.950
n-Octane	C_8H_{18}	114.23	20	0.704	101.6	1.190	6.45	0.000282	0.000347	1.230
Paraldehyde	$C_6H_{12}O_3$	132.16	18	0.994	88.2	1.075	6.04	0.000291	0.000355	1.220
Toluene	$C_6H_5CH_3$	92.13	30	0.862	96.5	1.103	5.62	0.000347	0.000355	1.023
Water	H_2O	18.02	30	0.996	47.9	1.457	3.104	0.001490	0.001470	0.987
o-Xylene	$C_6H_4(CH_3)_2$	106.16	20	0.875	79.7	1.207	5.87	0.000347	0.000372	1.070

[a] At 87 atm.

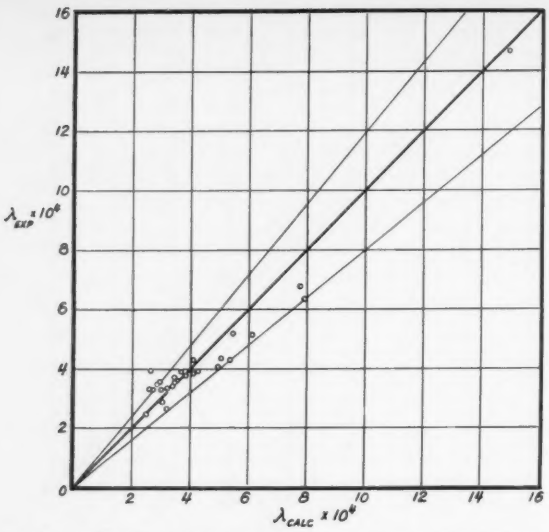

FIG. 3 COMPARISON OF CALCULATED, $\lambda_{calc.}$, AND EXPERIMENTAL, $\lambda_{exp.}$, VALUES OF THE THERMAL CONDUCTIVITY OF LIQUIDS. THE UNIT OF λ IS CAL/CM SEC °C.

As a further check on Equation [46], the variation of the thermal conductivity of water with temperature is computed and compared with the experiments. Since the ratio of specific heats for liquid water is very nearly equal to one, the velocity $1/\sqrt{\rho\beta}$ for water is in fact the velocity of sound c. Thus for water, the ratio of thermal conductivity at two temperatures designated by subscripts 1 and 2, is given by

$$\frac{\lambda_2}{\lambda_1} = \frac{c_2}{c_1}\left(\frac{\rho_2}{\rho_1}\right)^{2/3}$$

This relation is compared with experimental data on λ in Table 7 where 13 °C is taken as the lower comparison temperature. The ratios of conductivity at two higher temperatures of 19 and 31 °C check closely with the test values. Therefore Equation [46] can also predict satisfactorily correct temperature variation of the thermal conductivity.

TABLE 7 THERMAL CONDUCTIVITY OF WATER

Temperature, °C	$c \times 10^{-1}$ cm/sec[a]	ρ gr/cc	λ_{exp}, cal/sec °C cm	$\left(\frac{\lambda_2}{\lambda_1}\right)_{calc}$	$\left(\frac{\lambda_2}{\lambda_1}\right)_{exp}$
13	1.441	0.9994	0.001410	1.000	1.000
19	1.461	0.9984	0.001431	1.012	1.015
31	1.505	0.9954	0.001475	1.040	1.046

[a] Taken from Smithsonian tables.

For normal liquids, the compressibility β is given by Equation [31]; then Equation [46] reduces to

$$\lambda = \frac{3R}{N^{1/3}}\left\{\frac{RT_b}{M}\left(101.6 - 82.4\frac{T}{T_b}\right)\right\}^{1/2}\left(\frac{\rho}{M}\right)^{2/3} \quad \ldots\ldots [47]$$

Therefore the thermal conductivity of normal liquid can be calculated once the molecular weight M, the boiling temperature T_b, and the density are known. Since density decreases with temperature, Equation [47] shows that the conductivity of normal liquids also decreases with temperature. The increasing conductivity of water with temperature shown in Table 7 indeed indicates the anomality of water as a liquid.

Concluding Remarks

The properties of pure liquids studied in the preceding sections are properties at low pressures, i.e., at pressures below the critical pressure of the substance. Then the pressure of the liquid is not a parameter in the calculations. In fact, for normal liquids, the only essential parameter is the normal boiling temperature of the liquid. This parameter, together with the density and the molecular weight of the liquid, then determines the coefficient of thermal expansion, the compressibility, the specific heats, the velocity of sound, the viscosity, and the thermal conductivity. The required information for calculating the properties is thus generally available in the handbook.

From the point of view of physical mechanics of predicting macroscopic behavior of matter in bulk from microscopic behavior of the molecules, the remaining task is then the determination of the liquid density and the normal boiling temperature from the knowledge of the molecular structure. Since both of these quantities are related to the bimolecular interaction, the missing link is then a method of calculating the molecular interaction from the structural formula of the liquid molecules. The well-known theory of molecular interaction due to F. London and W. Heitler and others has unfortunately not yet been developed into a form useful for this purpose. Here clearly is a field for future research.

APPENDIX

Quantal Effects at Low Temperatures

S. D. Hamann (16) has investigated the quantal correction to the Lennard-Jones and Devonshire theory of liquids by approximating the spherical cage of the theory by a cube with a square-well potential. The size of the cube is determined by the diameter of the sphere within which the Lennard-Jones-Devonshire potential is negative. Let the ratio of this size to the molecular distance a be x. When $V \cong V^*$, as is the case for liquid at low pressures, $x \cong 0.2$. Hamann showed that the temperature T for appreciable quantal effects is given by the equation

$$\frac{2\pi mkT}{h^2}\left(\frac{4\pi}{3}\sqrt{2}\,V\right)^{2/3}x^2 \cong 1$$

where m is the mass of a molecule, k the Boltzmann constant, h the Planck constant, and V the volume of liquid per molecule. For N_2 molecule, if the density of the liquid is taken to be 0.8, this temperature for appreciable quantal effects is only 5.5 °K. Therefore it is certain that none of the anomalies in Table 5 can be due to quantum mechanical reasons.

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(*Continued on page 35*)

Effect of Vibrational Excitation on the Theoretical Performance of the Stoichiometric Carbon-Oxygen Propellant System

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Accurate calculations to evaluate the performance of the stoichiometric carbon-oxygen propellant system have been carried out for nozzle flow with and without chemical reactions and with and without vibrational adjustment. The calculations show that, for frozen chemical flow, a lag of vibrational energy states at chamber conditions nearly doubles the reduction in I_{sp}, as compared with flow in which complete vibrational equilibrium is maintained. On the other hand, lags in vibrational adjustment have practically no effect on the theoretical performance of hot propellant systems if chemical equilibrium is maintained during nozzle flow. The preceding conclusions are in agreement with the results on other propellant systems obtained previously by use of an approximate evaluation procedure.

I Introduction

IT IS well known that the over-all performance of rocket propellant systems is dependent on the extent to which physicochemical changes occur during nozzle flow. Thus it is customary to report specific impulse data for "equilibrium flow" (the chemical reactions are fast enough to maintain thermodynamic equilibrium at all times) and for "frozen flow" (the chemical composition remains unchanged at the concentrations corresponding to thermodynamic equilibrium in the combustion chamber). Practical experience has shown that this method of estimating reasonable upper and lower bounds for performance evaluation is generally in accord with experimental results.[2]

Implicit in the customary propellant evaluation procedures is the assumption that complete thermodynamic equilibrium is maintained during flow with respect to excitation of internal degrees of freedom. It is apparent, however, that sizable departures from equilibrium internal excitation may occur, for example, for the vibrational degrees of freedom, particularly for nonhydrogen-containing propellant systems in small motors for which the vibrational relaxation times may not be short compared to the residence time (1, 2).[3] Approximate estimates of the effect of vibrational excitation on performance of rockets have been carried out previously by Penner (3).

It is the purpose of the present analysis to present the first accurate evaluation of the probable combined effects of chemical and vibrational lags during nozzle flow. Performance calculations have been carried out for the following special cases: (*a*) Complete thermodynamic equilibrium is maintained (equilibrium flow). (*b*) Complete thermodynamic equilibrium is maintained with respect to internal energy states but no chemical reactions occur during nozzle flow (frozen flow). (*c*) Complete thermodynamic equilibrium is maintained except that no adjustments of vibrational degrees of freedom occur during flow (chemically equilibrium and vibrationally frozen flow). (*d*) Complete thermodynamic equilibrium is maintained except that no chemical reactions and no adjustment of the vibrational degrees of freedom occur during flow (chemically and vibrationally frozen flow).

II Basic Equations

The requisite basic equations for cases (*a*) to (*d*) have been given elsewhere (4). For the present purposes it will be convenient to express the chemical composition by the mole fractions for the various chemical species. In terms of mole fractions it is readily shown[4] that [7], [8], [11], and [12] of Reference (4) become, respectively:

(*a*) For equilibrium flow

$$\tfrac{1}{2}\,\bar{M}_c u_e^2 = \Delta H_{oe}^{oc} = \sum_{k=1}^{n} N_{ke}{}^{o} H_{oke} - (\bar{M}_c/\bar{M}_e) \sum_{k=1}^{n} N_{ke}{}^{o} H_{oke} \quad \ldots\ldots [1a]$$

(*b*) For frozen flow

$$\tfrac{1}{2}\,\bar{M}_c u_e^2 = \Delta H_{oe}{}^{c} = \sum_{k=1}^{n} N_{kc}{}^{o}\,[H_{okc} - H_{ke}] \ldots\ldots [1b]$$

(*c*) For chemically equilibrium and vibrationally frozen flow

$$\tfrac{1}{2}\,\bar{M}_c u_e^2 = \Delta H_{oe}{}^{oc} + (\bar{M}_c/\bar{M}_e) \sum_{k=1}^{n} N_{ke}{}^{o}\,[H_{oke}{}^{vib} - H_{oke}{}^{vib}] \quad \ldots\ldots [1c]$$

(*d*) For chemically and vibrationally frozen flow

$$\tfrac{1}{2}\,\bar{M}_c u_e^2 = \Delta H_{oe}{}^{c} + \sum_{k=1}^{n} N_{kc}{}^{o}\,(H_{ke}{}^{vib} - H_{kc}{}^{vib}) \ldots\ldots [1d]$$

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[1] Lieutenant, U. S. Navy. This paper is based on a thesis submitted to the graduate school of the California Institute of Technology, in partial fulfillment of requirements for the degree of Aeronautical Engineer, June 1952. The author is indebted to Dr. S. S. Penner for helpful suggestions throughout the course of the work.

[2] The usual simplifying assumptions in propellant evaluation, which do not involve consideration of rate processes, are the following: Thermodynamic equilibrium is reached in the combustion chamber after adiabatic reaction; expansion of the combustion products through the Laval nozzle is adiabatic; the products of combustion behave as ideal gases; the adiabatic expansion may be considered to involve one-dimensional flow (parallel to the nozzle axis) of nonviscous ideal gases; the velocity of the gases at the nozzle entrance position is negligibly small compared to that at the exit position. For further details concerning customary evaluation techniques see, e.g., "Quantitative Evaluation of Rocket Propellants," by S. S. Penner, *American Journal of Physics*, Vol. 20, 1952, pp. 26–31.

[3] Numbers in parentheses refer to the References on page 27.

[4] For the relatively simple case of flow with frozen vibrational energy states, it is not necessary to use the analysis given in (4) since [1a]-[1d] are obvious expressions for conservation of energy.

In [1a] to [1d], u_e represents the linear flow velocity at the nozzle exit position, N_{kc}° and N_{ke}° are the equilibrium mole fractions of species k evaluated at the chamber exit and nozzle exit positions, respectively; H_{kc}, H_{okc}, H_{ke}, and H_{oke} equal the total enthalpy (sensible plus chemical enthalpy) per mole of species k if complete internal equilibrium exists at the nozzle entrance and exit positions, respectively; the superscript *vib* signifies that only the vibrational enthalpy is involved; the subscript o denotes chemical equilibrium during flow; without the subscript o the flow process occurs without composition change ($H_{ke}^{vib} \equiv H_{oke}^{vib}$).

From [1a] to [1d] it is apparent that the evaluation of u_e and hence of $I_{sp} = u_e/g$ requires the calculation of equilibrium mole fractions N_{ke}° and N_{kc}° as well as of total and vibrational enthalpies. Since the exit temperature is determined by the assumption that the flow process is isentropic,[2] it is obvious that the exit temperature T_e, and hence the numerical values of N_{ke}°, H_{ke}, H_{ke}^{vib}, H_{oke}, and H_{oke}^{vib} will depend upon the assumed type of flow process.

III Outline of Calculations

For the stoichiometric solid-carbon gaseous-oxygen propellant system [1 mole of C(c) reacting with 1 mole of O_2 (g)] the equilibrium mole fractions at any temperature may be determined conveniently by writing the over-all chemical reaction in the form

$$C + O_2 \rightarrow (1 - x)\,CO_2 + x\,CO + [(x - y)/2]\,O_2 + yO$$

The values of x and y are given by the solution of the following pair of simultaneous equations

$$x^3(P_T + K_1K_2 - K_2^2) + x(3K_2^2 - K_1K_2) - 2K_2^2 = 0 \quad \ldots [2]$$

and

$$y = K_1x^2[x(K_1 - 2K_2) + 2K_2]^{-1} \quad \ldots [3]$$

where P_T represents the total pressure and the equilibrium constants,[5] K_1 and K_2 are defined, respectively, by the relations $K_1 = P_O/(P_{O_2})^{1/2}$ and $K_2 = P_{CO}(P_{O_2})^{1/2}/P_{CO_2}$.

Using appropriate values (5) for K_1 and K_2, the equilibrium chamber temperature T_c was found to be 3750°K for $P_T = 20$ atm using standard procedures for the calculation of the adiabatic flame temperature (6). The mole fractions and average molecular weights $\bar{M}$ are given at 3750°K and $P_T = 20$ atm, and at various temperatures for $P_T = 1$ atm, in Table 1.

TABLE 1 EQUILIBRIUM MOLE FRACTIONS N_k° AND AVERAGE MOLECULAR WEIGHTS $\bar{M}$ AS A FUNCTION OF PRESSURE AND TEMPERATURE FOR THE STOICHIOMETRIC CARBON-OXYGEN PROPELLANT SYSTEM

T, °K	P_T, atm	N_{CO_2}	N_{CO}	N_{O_2}	N_O	$\bar{M}$
3750	20	0.2900	0.4443	0.1787	0.0870	32.3
3250	1	0.2502	0.4631	0.1762	0.1106	31.39
3000	1	0.4283	0.3652	0.1587	0.0479	34.91
2750	1	0.6190	0.2480	0.1150	0.0160	38.09

A Equilibrium Flow

Equilibrium flow calculations have been carried out in the usual way.[2] For equilibrium flow it is found that $T_e = 2970$ °K, $u_e = 2.220 \times 10^5$ cm/sec, $I_{sp} = 227$ sec.

B Frozen Flow

For frozen flow it is found[2] that $T_e = 2110$° K, $u_e = 2.105 \times 10^5$ cm/sec, $I_{sp} = 215$ sec.

[5] The effect of lag in vibrational energy states on the equilibrium constants has been neglected. It can be shown that the changes in equilibrium constant will not affect the numerical values obtained in the present calculations (cf. AE thesis of J. H. Schroeder, California Institute of Technology, Pasadena, 1952).

C Chemically Equilibrium, Vibrationally Frozen Flow

For chemically equilibrium but vibrationally frozen flow, the isentropic relation which is used to determine T_e becomes

$$\sum_{k=1}^{n} N_{kc}^{\circ}(S_{kc}^{\circ} - R \ln P_c - R \ln N_{kc}^{\circ}) = (\bar{M}_c/\bar{M}_e) \sum_{k=1}^{n} N_{ke}^{\circ}[S_{ke}^{\circ} - R \ln P_e - R \ln N_{ke}^{\circ} - (S_{ke}^{vib} - S_{kc}^{vib})] \quad \ldots [4]$$

where S_{kc}° and S_{ke}° denote the total molar entropies at the chamber and exit conditions, respectively; the superscript *vib* indicates that only the vibrational entropy is involved; R is the molar gas constant.

For diatomic molecules the vibrational contribution to the entropy is, in good approximation (7)

$$S^{vib} = R\{u[\exp(u) - 1]^{-1} - \ln[1 - \exp(-u)]\} \quad \ldots [5]$$

Here $u = hc\omega^*/kT$, h represents Planck's constant, c is the velocity of light, k the Boltzmann constant, and ω^* the wave number corresponding to an energy transition from the ground vibrational energy level to the first excited vibrational state for the nonrotating diatomic molecule. For the linear triatomic molecule CO_2, the total vibrational entropy is given by the approximate relation (7)

$$S^{vib} = R \sum_{i=1}^{4} \{u_i[\exp(u_i) - 1]^{-1} - \ln[1 - \exp(-u_i)]\} \quad \ldots [6]$$

where u_i corresponds to the four normal vibration frequencies of CO_2. For the present calculations, the numerical values of the characteristic temperatures $\theta = hc\omega^*/k$ which are listed in Table 2 were used.

TABLE 2 CHARACTERISTIC TEMPERATURES FOR O_2, CO, AND CO_2

Molecule	O_2	CO	CO_2
θ, °K	2228	3067	955.6, 955.6, 1925, 3493

The left-hand side of [4] is found to be 67.65 cals/°K mole at $T_c = 3750$°K; the right-hand side of [4] is found to be 67.557 at $T_e = 2900$°K, 69.012 at $T_e = 3000$°K, and by linear interpolation it is found that $T_e = 2910$°K.

For diatomic molecules the vibrational contribution to the enthalpy is in good approximation (7)

$$H^{vib} = RTu[\exp(u) - 1]^{-1} \quad \ldots [7]$$

For the linear triatomic molecule CO_2 the total vibrational enthalpy is given by the approximate relation

$$H^{vib} = RT \sum_{i=1}^{4} u_i\,[\exp(u_i) - 1]^{-1} \quad \ldots [8]$$

Using these relations, the values for H^{vib} (in cal/mole) listed in Table 3 were obtained.

TABLE 3 H^{vib} AS A FUNCTION OF TEMPERATURE FOR O_2, CO, AND CO_2

	{H^{vib} (cal/mole) at}		
Molecule	3750°K	3000°K	2900°K
O_2	5455.8	4018.0	3829.3
CO	4815.0	3423.6	3242.6
CO_2	23,247	17,424	16,869

For case (*a*) we find that $\Delta H_{oe}^{oc} = +22.26$ kcal/mole at $T_e = 2910$° K, whence it follows that $\frac{1}{2}M_cu_e^2 = \Delta H_{oc}^{e} = 18.72$ kcal/mole, $u_e = 2203$ meters/sec, and $I_{sp} = 225$ sec.

D Constant-Composition and Vibrationally Frozen Flow

For constant-composition and vibrationally frozen flow the isentropic relation, which is used to determine T_e, becomes

$$\sum_{k=1}^{n} N_{kc}^{\circ}[S_{okc}^{\circ} - S_{oka} - (S_{kc}^{vib} - S_{ke}^{vib})] = R \ln \frac{P_c}{P_e} \quad \ldots [9]$$

By trial and error calculation we find that $T_e = 1600°K$. By use of [1d] and [7] it is readily shown that $^1/_2\bar{M}_e u_e^2 = \Delta H_e^c = 15.144$ kcal/mole, $u_e = 1981$ meters/sec, and $I_{sp} = 202$ sec.

In using [5] to [8] we assumed harmonic oscillations. It can be shown (7) that satisfactory approximations to the anharmonicity correction terms are

$$S^{vib}_{k\ (corr)} = R\,\frac{4u^2e^u x}{(e^u - 1)^3} \cdots\cdots\cdots\cdots [5a]$$

and

$$H^{vib}_{k\ (corr)} = RT\left[\frac{4u^2xe^u}{(e^u - 1)^3} - \frac{2ux}{(e^u - 1)^2}\right] \cdots [7a]$$

Detailed calculations show that inclusion of corrections obtained from [5a] and [7a] does not change the numerical values summarized in Table 4.[6]

TABLE 4 SUMMARY OF RESULTS

Type of Flow	T_e, °K	u_e, m/s	I_{sp}, sec
Chemically equilibrium and energy-equilibrium flow	2970	2220	227
Chemically frozen and energy-equilibrium flow	2110	2105	215
Chemically equilibrium and vibrationally frozen flow	2910	2203	225
Chemically frozen and vibrationally frozen flow	1600	1981	202

IV Discussion of Results

Reference to Table 4 shows that the effect of vibrationally frozen flow is of no consequence when chemical equilibrium is maintained. In this case, lag in vibrational adjustment lowers the performance by roughly one per cent.

On the other hand, the effect of vibrationally frozen flow for frozen chemical flow is such as to decrease *Isp* approximately six per cent. In this connection it is of interest to note that lags in vibrational adjustment, for a given propellant system, become more likely as the nozzle size is reduced because a reduction in nozzle size means increased cooling rates. In particular, it has been postulated that frozen-vibrational flow occurs in the small nozzles used in the pneumatic method for measuring temperatures in combustion chambers (8).

The calculations on the carbon-oxygen propellant system have been repeated by using Penner's approximate procedure (3) which permits ready estimates of the effect of vibrational lag on performance for propellant systems for which the usual theoretical performance data are available. The results of these calculations are summarized in Table 5, together with data for other propellant systems which were obtained by utilizing the concept of a constant average vibrational heat capacity during flow (3). Reference to Table 5 shows that lag in vibrational energy states produces a similar effect on performance for widely different propellant systems. A simple physical explanation for this observation is obtained by noting that frozen vibrational flow reduces the effective heat capacity during expansion by nearly the same extent for chemically frozen and for chemically equilibrium flow. On the other hand, the effective heat capacity is much larger for flow in which chemical changes occur, provided the propellant system is sufficiently hot. Hence the effect of vibrational lags will always be more pronounced for flow without chemical change than for chemically equilibrium flow. Furthermore, the disparity will be largest for the hottest propellant systems. The preceding remarks are obviously in accord with the data given in Table 5, which show a large effect of vibrational lag on performance for chemically equilibrium flow only for the relatively cool RFNA-aniline propellant system.

TABLE 5 EFFECT OF LAG IN VIBRATIONAL ENERGY STATES ON PERFORMANCE FOR VARIOUS PROPELLANT SYSTEMS

Propellant system	I_{sp} (energy equilibrium flow) ÷ I_{sp} (vibrationally frozen flow) for— Equilibrium flow	Frozen flow
Carbon-oxygen[a]	1.009	1.064
Carbon-oxygen[b]	1.01	1.06
Hydrogen-fluorine[c]	1.008	1.034
Hydrogen-oxygen[c]	1.006	...
RFNA-aniline[c]	1.032	1.056

[a] Accurate calculations.
[b] Approximate calculations.
[c] Results given in (3).

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[6] This statement should not be interpreted to mean that the vibrational entropies and enthalpies for CO_2 are given accurately by using harmonic oscillator approximations with anharmonicity corrections. Calculation utilizing the known energy levels of CO_2 to determine the partition function raises an interesting question concerning the assignment to vibration or rotation of the quantized angular rotation associated with the doubly degenerate ν_2-vibration. It is perhaps most reasonable to express the total energy of the CO_2-molecule as $W = W_V(n_1, n_2, n_3, l) + W_R(j)$, where W_V and W_R denote the vibrational and rotational energy levels, respectively; n_1, n_2, and n_3 are vibrational quantum numbers, l is the quantum number for angular rotation associated with the ν_2-vibration, and j is the rotational quantum number. Detailed numerical calculations have been carried out utilizing the energy levels of Adel and Dennison (see, e.g., D. M. Dennison, *Reviews of Modern Physics*, vol. 12, 1940, pp. 175–214). These laborious calculations show that the required corrections to S_{vib} and H_{vib} for CO_2 are not small at the temperatures of interest for the present analysis. Nevertheless, the effect on over-all performance is negligibly small. For this reason an outline for the more exact work, which would necessarily be lengthy, is not included in the present discussion.

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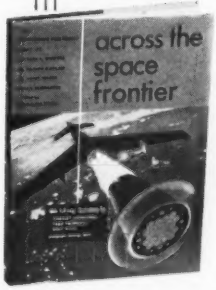

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Some Experiments on Flow Separation in Rocket Nozzles[1]

KARL SCHELLER[2] and JAMES A. BIERLEIN[2]

Wright Air Development Center, Dayton, Ohio

Flow separation in de Laval nozzles has been investigated experimentally over a range of divergence angles and reservoir pressures using compressed air as a working fluid. The results indicate that the onset of separation in such nozzles is governed primarily by the reservoir pressure and the nozzle divergence angle. However, no quantitative treatment has been evolved to unify all the existing experimental data. Further experimental work, or a more sophisticated interpretation of available facts, is needed to establish a theory for predicting the plane of separation for a nozzle of given geometry operated under specified conditions.

Introduction and Scope

IT HAS been known for a long time that there is a limit to the extent to which isentropic flow will persist in a convergent-divergent nozzle as the geometric and operating parameters of the system are varied. Stodola's classic treatise on turbines (1)[3] presents some curves showing this effect in steam nozzles, and some early investigations at the California Institute of Technology indicated that the validity of the isentropic thrust coefficient for rockets, as developed by Malina and Tsien (2), is influenced by the nozzle divergence angle. More recent experiments on rocket nozzles have been reported by Summerfield, Foster, and Swan (3) of the California Institute of Technology, and by various workers at the Aerojet Engineering Corporation incidental to classified projects. However, no completely general development of the theory of such flow degeneration has ever been made, despite the appreciation of the fact that this phenomenon can and does exert appreciable effects on the performance of rockets. A rational understanding of this process, permitting it to be forecast accurately in advance or to be harnessed to advantage as suggested by Summerfield (4), would constitute a practical advance as well as a satisfying academic achievement. It is proposed in this paper to contribute some new experimental data which may aid in the ultimate attainment of this goal.

Separation in nozzles may be defined as a breakdown of isentropic flow characterized by a departure of the main gas stream from the nozzle surface. The cross section at which this process takes place may be designated, for convenience, as the separation station. Upstream of the separation station, an isentropic expansion is in progress. At the separation station itself, abrupt changes occur in the state properties of the gas, and the entropy of the gas must thereby increase. Physical detachment of the flow from the nozzle wall at this point has actually been observed by shadow photography (5). Downstream of the separation station, the pressure is slightly below ambient but appears to rise gradually, just attaining the ambient value as the gas reaches the exit station.

Only meager experimental data are available relative to the phenomenon of separation. There exists a need for a more extensive range of data before it can be hoped to test any hypothesis which might ultimately lead to a rational treatment of this effect. We present herewith some new data and a critical survey of the present status of the field, but the desired rational treatment yet remains to be achieved.

Experimental Procedure

The experimental program was designed to obtain quantitative data at higher pressure ratios and more extreme nozzle geometries than had previously been investigated. The procedure used in this work consisted in exhausting compressed air from a high pressure source into ambient air through a test nozzle instrumented to provide a history of the pressure along the entire length of the nozzle wall. A schematic diagram of the test apparatus is shown in Fig. 1. Compressed air was stored over phosphorus pentoxide in two torpedo air flasks which were charged to 2500 psia from a compressor. The air flowed in parallel lines, through a high pressure shut-off valve, and into a bank of two-

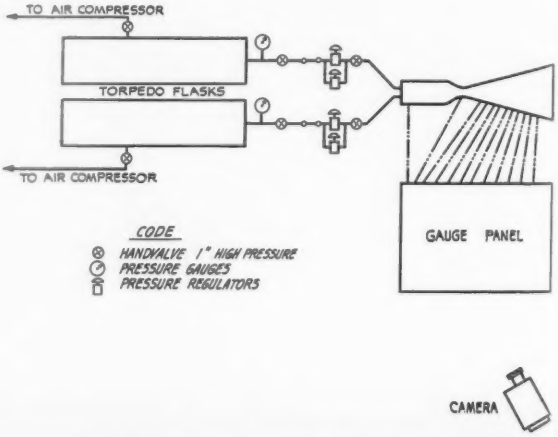

FIG. 1 SCHEMATIC DIAGRAM OF APPARATUS

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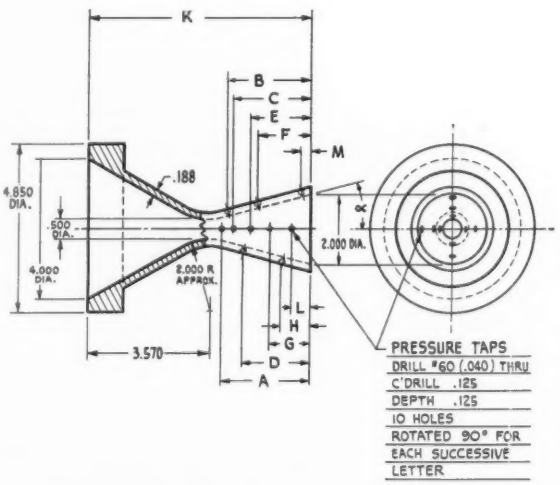
[1] Presented at the Annual Meeting of the AMERICAN ROCKET Society, New York, N. Y., November 30, 1950.

[2] Research Engineer, Flight Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio.

[3] Numbers in parentheses refer to the Bibliography on page 40.

pressure regulators in parallel. Then it was passed through a needle-throttling valve into a plenum chamber from which it was exhausted to the atmosphere. The valves upstream of the regulators were inserted for rapid shut-off purposes. The regulators would ideally maintain a constant downstream pressure, adjusted to the desired settling chamber or reservoir pressure by means of the needle valves. In actuality, the system exhibited a natural tendency toward gradual decay of chamber pressure during the course of an average run (about 60 sec duration). This characteristic was turned to advantage by taking continuous pressure measurements on the nozzle over the range of transient reservoir pressures. In this manner, more data were obtained for a given quantity of compressed air than would have been possible with tests at a series of constant reservoir pressures. The rate of decay of general pressure level in the system was sufficiently slow so that any set of simultaneous measurements could be treated as a steady-state condition without appreciable error.

The test apparatus was constructed from miscellaneous equipment at hand in the laboratory. The torpedo air flasks were of the Mark IV type, each having a volume of approximately 39 cubic feet and an outlet pipe connection 1 in. in diam. The small size of the outlet made it necessary to use the dual flow system shown in order to secure the desired mass flow of air. The combustion chamber of an obsolete pressure-fed rocket (Aerojet Model AL-1000) was employed as a calming chamber. The injector was left in the chamber to serve as an air distributor and to insure a uniform reservoir pressure prior to the entry of air into the nozzle. The fuel manifold of the injector was connected to one of the air flasks and the oxidizer manifold was connected to the other.



DASH NO.	NOZZLE HALF ANGLE ° α	OVERALL LENGTH	K	A	B	C	D	E	F	G	H	L	M
1	5	12.18	7.46	6.96	6.54	5.76	5.06	4.46	3.37	2.43	1.55	0.77	
2	15	6.43	2.56	3.40	2.25	1.99	1.76	1.55	1.19	0.87	0.57	0.30	
3	25	5.31	1.46	1.37	1.29	1.14	1.01	0.91	0.70	0.53	0.36	0.21	
4	33	4.81	1.04	0.97	0.92	0.82	0.74	0.65	0.52	0.40	0.28	0.18	

FIG. 2 NOZZLES USED IN EXPERIMENTAL TESTS

Four nozzles were fabricated for these tests with nominal diverging half-angles of 5, 15, 25, and 35 deg. Each had an expansion ratio of 16, corresponding to a pressure ratio of 200. A drawing of the nozzles is shown in Fig. 2. The length of each nozzle was dependent upon its divergence angle. A total of 11 pressure taps was provided for each nozzle. These included one throat tap and ten nozzle wall taps located according to a nominal expansion ratio schedule of 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 8.0, 10.0, 12.0, and 14.0. The taps were drilled with a #60 bit and counterbored with an 0.125-in. flat-bottomed drill to a depth of 0.125 in., to enable pressure pickup lines to be welded to the nozzle at each tap. After fabrication, the exact divergence angles of the nozzles were measured and the diameters at the throat and at each of the pressure taps were checked to determine the actual expansion ratio at each pressure station. All of these lines were piped to a

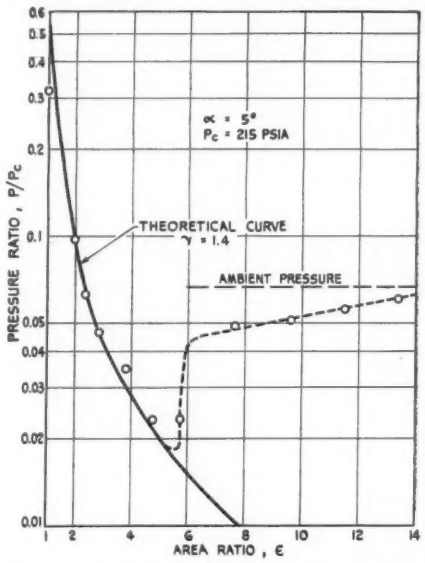


FIG. 3 TYPICAL PLOT OF EXPERIMENTAL DATA

common instrument board containing Bourdon-tube pressure and vacuum gages. In all, 12 gages were installed in the board, one to measure chamber pressure and the remaining 11 to measure nozzle pressures. A motion picture camera recorded the gage pressures continuously during each run, thus affording a complete time history of reservoir pressure against nozzle pressure at the various area ratios.

Since the critical temperature for air is 132 K, a calculation was made to determine whether it might liquefy at any combinations of pressure and temperature within the nozzle. Such an event would obviously be disastrous to the purposes of these experiments. The condensing temperature of air was computed as a function of pressure, using published vapor-pressure data on oxygen and nitrogen and assuming Raoult's law. Under the most adverse conditions of operation theoretically possible (isentropic expansion and a maximum stagnation pressure of 600 psia), incipient liquefaction of air should not be encountered in these nozzles

below an area ratio of 11. It was expected that separation would be encountered before the air would be expanded into the two-phase region, and this proved to be the case in the experiments.

A series of ten runs was conducted with the four nozzles to cover a range of reservoir pressures varying from approximately 100 to 600 psia. All test data were recorded continuously on film at a rate of 8 frames per sec. Simultaneous values of stagnation (chamber) pressure and survey station pressures were then read from the film for a series of conveniently selected reservoir pressures. A typical set of test data, reduced to graphical form by plotting the ratio of the pressure along the nozzle to the stagnation pressure as a function of area ratio, is depicted in Fig. 3 for the 5-deg nozzle. For ready comparison between the observed pressure ratios and the values predicted for isentropic expansion assuming no separation, the theoretical expansion line is shown in this illustration.

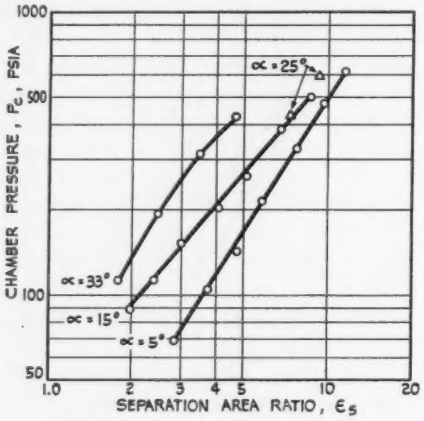


FIG. 4 CHAMBER PRESSURE AGAINST SEPARATION STATION AT CONSTANT DIVERGENCE ANGLE. AUTHORS' DATA

It is seen that the gas in the nozzle expands in reasonable accord with theory until separation occurs, after which the pressure increases with increasing area ratio. Although this method of presenting the data is instructive for purposes of visualization, it is not well suited to the exact determination of the separation station. It is apparent that the precise location of the area ratio at which separation occurs will depend to a great extent upon the type of curve drawn through the experimental points. In Fig. 3, for example, the separation station may lie anywhere between an area ratio of about 5 to 6 and cannot be accurately determined from the plot. In order to eliminate the uncertainties inherent in this method of data reduction, another procedure was devised to accomplish this purpose with much greater accuracy.

Inasmuch as the chamber pressure was slowly changing during an experiment, it is a necessary corollary that the separation station was likewise moving along the nozzle, crossing each of the pressure survey stations in turn. Hence, at any particular pressure survey point the pressure would sharply increase as soon as the separation front passed across it. By examining the films from each test, frame by frame, it was easy to ascertain the exact reservoir pressure at which the separation wave crossed each pressure survey station. The results obtained in this manner are shown in Table 1. The data are plotted in Fig. 4 and have been faired-in with smooth curves for three of the nozzles. No curve has been drawn through the two points representing the experimental results for the 25-deg nozzle. This nozzle was damaged beyond repair during test; the two points shown may be of questionable reliability. Some points were also lost on the 33-deg nozzle due to inadvertent closure of the pressure taps when the pressure take-off lines were welded to the nozzle.

Discussion of Data

Fig. 5 is a summary of prior data obtained by the California Institute of Technology and the Aerojet Engineering Corporation; the curves are the lines of best fit recommended by these organizations for their

TABLE 1 SUMMARY OF AUTHORS' DATA FOR ALL NOZZLES

Divergence angle, deg	Chamber pressure, P_c, psia	Separation area ratio
5	635	11.5
	475	9.60
	335	7.64
	215	5.72
	145	4.74
	105	3.80
	70	2.83
15	500	8.62
	395	6.85
	265	5.10
	205	4.13
	155	3.28
	115	2.40
	90	1.98
25	595	9.40
	435	7.33
33	415	4.68
	315	3.55
	195	2.51
	115	1.80

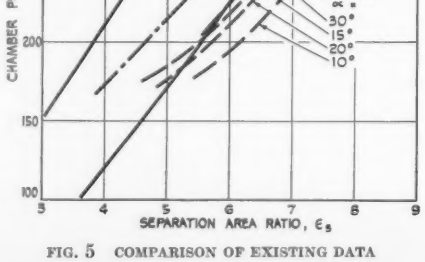


FIG. 5 COMPARISON OF EXISTING DATA

experimental points. Because of their greater range, our own data cannot be depicted in their entirety on the same graph; but those parts of our measurements which lie in the same region have been included for comparison. It can be seen that the three sets of data are not in good agreement. This is perhaps not too surprising; although all these data were taken at the same ambient pressure (atmospheric), most of the other principal characteristics of the system were at variance. These characteristics are summarized in Table 2. It may be seen that the working fluids differed in composition as well as in temperature level; furthermore, there was a difference in the physical scale of the experiments as indicated by the nozzle throat diameters. Another difference, not shown in the table, is that Aerojet used a tubular chamber in which the velocity of approach to the nozzle inlet is not negligible, whereas plenum chambers were used in the rest of the experiments.

We have not included in our comparison some recent data obtained at California Institute of Technology on a two-dimensional nozzle with nitrogen as a working fluid, since the separation characteristics of this nozzle were quite similar to those of three-dimensional nozzles. A few of these tests, made at a back pressure twice atmospheric, indicated that the location of the separation station may be insensitive to the ambient pressure.

TABLE 2 EXPERIMENTAL CONDITIONS USED BY VARIOUS INVESTIGATORS

	Calif. Inst. of Technology	Aerojet Engng. Corp.	Authors
Propellant	RFNA-aniline	Oxygen-hydrogen	Air
Mixture ratio, O/F	1.9	5.3	....
Chamber temp., °K	2200	3300	300
C_p/C_v, approx.	1.25	1.30	1.40
Molecular wt of chamber gas	26.5	12.7	29.0
Nozzle throat diam, in.	1.55	1.14	0.50
Viscosity of chamber gas, lb/ft sec	4.0×10^{-5}	6.0×10^{-5}	1.2×10^{-5}
Divergence angles used, deg	10, 15, 20, 30	15	5, 15, 25, 33

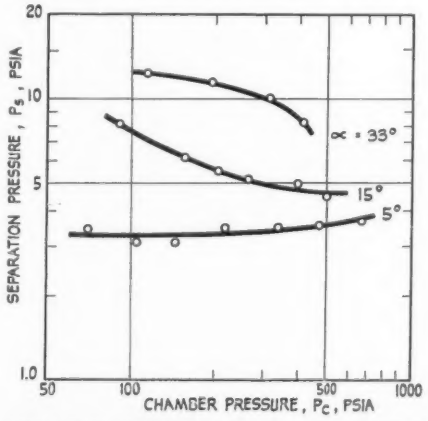


FIG. 6 SEPARATION PRESSURE AGAINST CHAMBER PRESSURE AT CONSTANT DIVERGENCE ANGLE. AUTHORS' DATA

There are some peculiarities in the CIT data which are worthy of attention; viz., the curve for their 20-deg nozzle lies between those for the 10 and 15-deg nozzles, although all three of these curves are nearly parallel. Their measurements on a 30-deg nozzle scatter somewhat, but are best represented by a line which straddles the other three. On the other hand, our curves progress in an orderly fashion with changing divergence angle, which is perhaps more in line with what one would expect beforehand. However, these observations are not necessarily an index to the quality of the respective experiments; there is no apparent reason to question the reliability of either set of data. Unfortunately, the Aerojet experiments were made only at a single divergence angle; it would be interesting to know whether the CIT inversion could be duplicated in their system also, since their apparatus and working fluid resemble those of CIT more closely than those used in our experiments.

Previous attempts to construct a theory which would explain separation phenomena have been preliminary in nature and generally inadequate; our new data serve to emphasize further the unsatisfactory status of present theoretical development in this field. The workers at the California Institute of Technology, who made the pioneer separation experiments in rockets, were the first to propose some general rules; these are based only on their own data as just presented. They preferred to ignore the effect of divergence angle (which is indeed rather small according to their measurements) and suggested the use of a single line, passing centrally through all their points, as a practical guide in correlating separation area ratio with chamber pressure. They also observed that they obtained separation when the pressure of the expanding gas attained a value amounting to about 0.4 times the ambient pressure; hence it is implied that separation is peculiar to overexpanded jets. In the light of the data now at hand, it would seem that neither of these criteria is generally valid. Figs. 4 and 5 show directly that divergence angle is sometimes a significant variable and that a single mean curve has no wide applicability. The rule regarding separation pressure also seems to be untenable as a generality. Fig. 6 shows our data on separation pressure, which varied both with chamber pressure and divergence angle in our experiments; all of the CIT data, if plotted on the same graph, would lie on the curve for our 15-deg nozzle. Hence the postulated constancy of the ratio of separation pressure to ambient pressure was not confirmed in our system. Indeed, it does not appear necessary that this ratio must always be less than unity, and the best supporting evidence for this is, in fact, afforded by subsequent experiments conducted at CIT, in which separation was observed in correctly expanded nozzles having divergence angles of 30 deg or more. Our present data show an interesting confirmation of this, although we did not directly observe any underexpanded separations. In Fig. 7 our separation data have been cross-plotted to show divergence angle as a coordinate rather than the parameter.

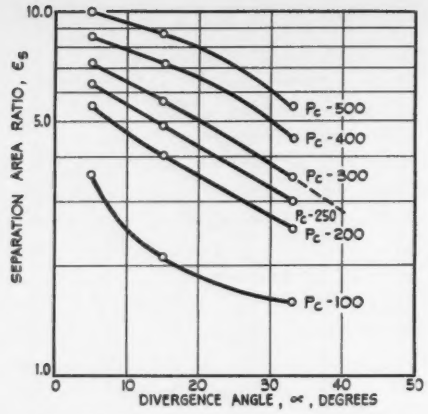


FIG. 7 SEPARATION AREA RATIO AGAINST DIVERGENCE ANGLE AT CONSTANT CHAMBER PRESSURE. AUTHORS' DATA

Now if the curve for 300-psia chamber pressure is extrapolated to a divergence angle of 40 deg, it predicts separation at an area ratio just below 3; this corresponds to separation of an underexpanded jet, since the correct expansion area ratio is about 3.5 for this chamber pressure. Our data suggest that there is a characteristic divergence angle for every chamber pressure, at which separation occurs at ambient pressure and which is the demarcation between overexpanded and underexpanded separation. Our experiments did not include sufficiently high divergence angles to permit the locus of these points to be determined except by an uncertain extrapolation; however, it seems fairly evident that such an effect exists in our system. We do not propose any new generalizations based on our experiments; but we believe that present criteria for predicting separation are oversimplified.

The CIT group has made an effort to construct a simple model to explain their findings. They proceed on the assumption that the separation is accompanied by an inclined shock wave which raises the pressure to the ambient value and turns the streamlines adjacent to the wall toward the nozzle axis. This is equivalent to inserting in the flow a body of revolution having as its cross section a wedge lying along the nozzle wall with its base parallel to the nozzle axis and its apex at the separation station. It has not been possible to correlate the new data for air with this model in any reasonable way.

Reliable engineering treatment of the flow breakdown awaits the development of a fundamental theory to explain observed phenomena. Such a theory must probably await the accumulation of more data, including a more systematic investigation of the influence of variable ambient pressure than is now available.

Acknowledgments

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(*Continued on page 40*)

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Technical Notes

Flow Separation in Rocket Nozzles

LEON GREEN, JR.[1]

Aerojet Engineering Corporation, Azusa, Calif.

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In accordance with the experimental results mentioned above, criteria for jet detachment in nozzles based upon a critical value of the ratio of the static pressure at the point of separation (p_s) to the surrounding atmospheric pressure (p_a) are often cited in the literature. Subsequent investigations, however, have revealed that the critical ratio p_s/p_a is not a true constant, but may be a function of the ratio of chamber pressure to atmospheric pressure (p_c/p_a) prevailing during the experiment. The experimental results obtained by various investigators (6, 7, 8, 9, 10), using axially symmetric nozzles with exit cones of 15-deg divergence half angles, are assembled in Fig. 1, from which it can be seen that the conditions sufficient to cause separation are not well represented by the

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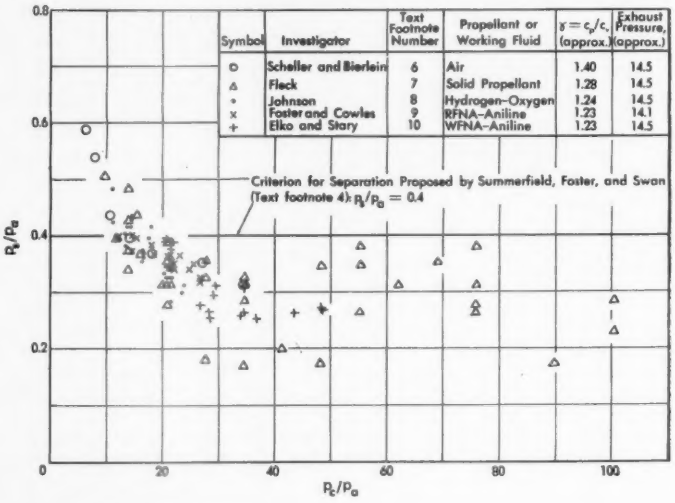
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+ | Elko and Stary | 10 | WFNA–Aniline | 1.23 | 14.5
Criterion for Separation Proposed by Summerfield, Foster, and Swan (Text footnote 4): $p_s/p_a = 0.4$
p_s/p_a
p_c/p_a
0
0.2
0.4
0.6
0.8
20
40
60
80
100

FIG. 1

FLOW-SEPARATION DATA OBTAINED BY VARIOUS INVESTIGATORS (DIVERGENCE HALF-ANGLE = 15°)

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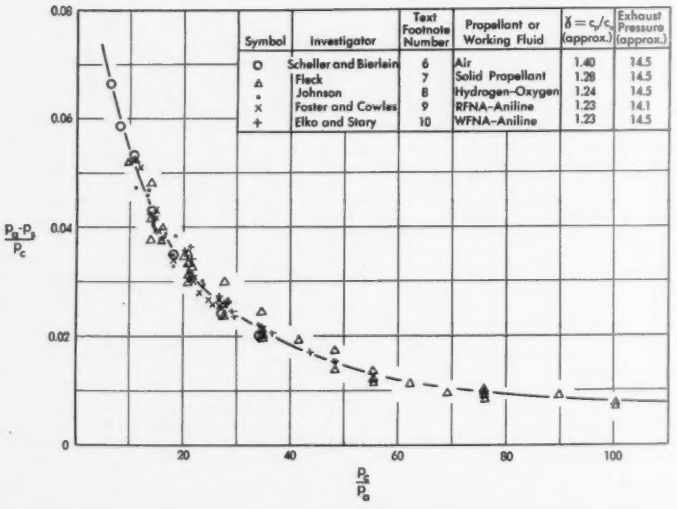
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+ | Elko and Stary | 10 | WFNA–Aniline | 1.23 | 14.5
$\frac{p_a - p_b}{p_c}$
$\frac{p_c}{p_a}$
0
0.02
0.04
0.06
0.08
20
40
60
80
100

FIG. 2

FLOW-SEPARATION DATA OBTAINED BY VARIOUS INVESTIGATORS (DIVERGENCE HALF-ANGLE = 15°)

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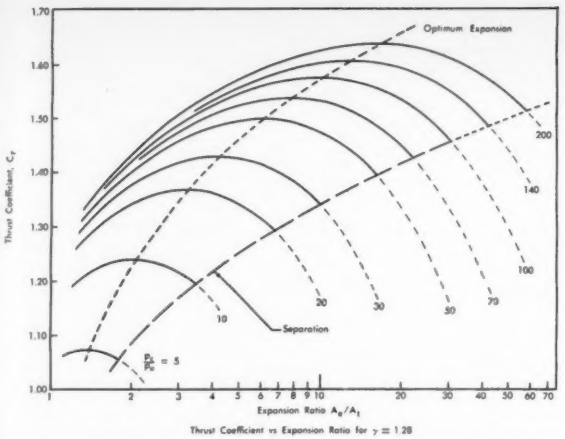

FIG. 3 THRUST COEFFICIENT VS. EXPANSION RATIO (POINT OF SEPARATION INDICATED)

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4 "The Mathematical Theory of Non-Uniform Gases," by S. Chapman and T. G. Cowling, Cambridge University Press, 1939.

5 See, for instance, the forthcoming book, "Properties of Gases," by J. O. Hirschfelder, C. F. Curtiss, R. B. Bird, and E. L. Spotz. The manuscript of this book was issued by the authors as reports of the Naval Research Laboratory, Department of Chemistry, University of Wisconsin.

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10 See, for instance, "The Transport Properties at High Densities," chapter in the book "The Properties of Gases," by J. O. Hirschfelder, C. F. Curtiss, R. B. Bird, and E. L. Spotz, issued as report of the Naval Research Laboratory, Department of Chemistry, University of Wisconsin, 1951.

11 See, for instance, "Kinetic Theory of Gases," by L. Loeb, McGraw-Hill Book Co., Inc., New York, 1927, p. 240.

12 "Heat Conduction in Alloys at Low Temperatures," by I. Estermann and J. E. Zimmerman, *Journal of Applied Physics*, vol. 23, 1952, pp. 578–588.

13 "The Thermal Conductivity of Metals," by R. E. B. Makinson, *Proceedings of the Cambridge Philosophical Society*, vol. 34, 1938, pp. 474–477.

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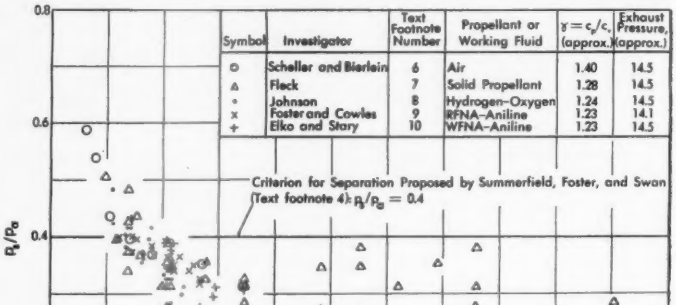
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p_c/p_a
0.8
0.6
0.4
0.2
0
20
40
60
80
100

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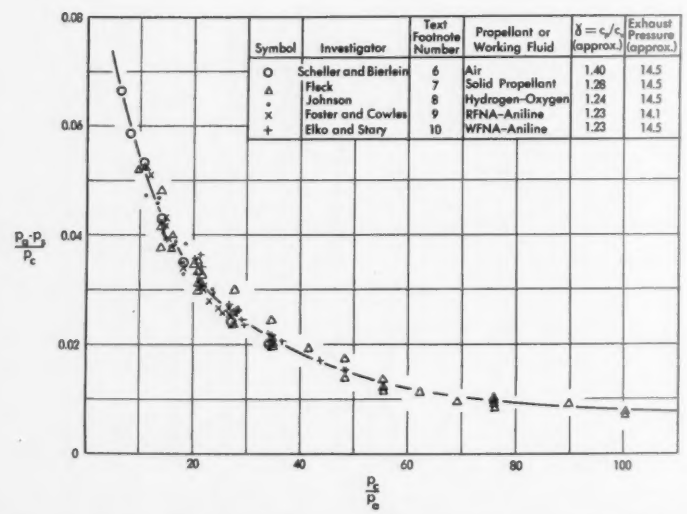
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$\frac{p_a - p_s}{p_c}$
$\frac{p_c}{p_a}$
0.08
0.06
0.04
0.02
0
20
40
60
80
100

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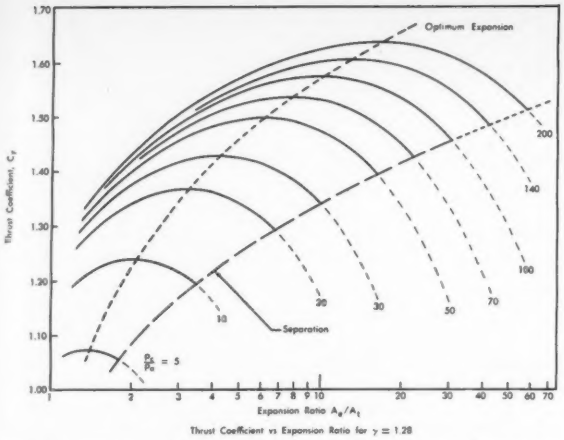

Thrust Coefficient vs Expansion Ratio for $\gamma = 1.28$

FIG. 3 THRUST COEFFICIENT VS. EXPANSION RATIO (POINT OF SEPARATION INDICATED)

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(*Continued from page 16*)

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Jet Propulsion News

C. F. WARNER, Purdue University, *Associate Editor*

with the assistance of W. G. BOHL and L. L. SCHILB

Rockets and Missiles

THE sequence of photographs shown in Figs. 1 and 2 show a Lockheed F-94C Starfire firing a burst of Aeromite 2.75-in. rockets. Fig. 1 shows the rockets just emerging from their firing tubes, and Fig. 2 shows the rockets well ahead of the F-94C. The F-94C also carries rockets in its wing pods. The use of the wing-tip pods provides improved dispersal of rockets since two more sources of firepower are provided. Firing of these wing tip rockets does not interfere with the vision of the pilot and radar observer at the critical moment of interception, and the turbojet engine air intakes are not exposed to smoke and debris produced by rocket firing. All twelve of the 2.75-in. rockets carried in these pods can be fired in less than one quarter of a second.

THE USAF is currently specifying the Hughes Aircraft Company's Falcon as its standard air-to-air guided missile for use on its new all-weather fighters and supersonic interceptors. The Falcon, a solid fuel rocket, has a maximum speed of Mach 3 and is equipped with an internal target homing guidance system. The Falcon will be carried externally on the jet planes.

✦ ✦ ✦

IT is reported that Britain is now developing a large number of guided missiles powered by ramjets, rockets, and pulsejets. The test models will be fired at the Australian Woomera desert range. A picture, Fig. 3, of a firing of one of the missiles reveals a medium-sized rocket leaving an inclined ramp with the assistance of eight solid booster units. The

FIG. 1.

LOCKHEED F-94C STARFIRE

FIRING AEROMITE ROCKETS

FIG. 2.

ROCKETS AFTER EMERGING

FROM STARFIRE

EDITOR'S NOTE: The information reported in this Section has been selected from approved news releases originating with the Department of Defense, private manufacturers, universities, etc., and from published news accounts in journals and newspapers. The reports are considered generally reliable, although no attempt has been made to verify them in detail.

FIG. 3 FIRING OF BRITISH MISSILE AT AUSTRALIAN WOOMERA RANGE

missile is said to travel at a speed of over 2000 mph to an altitude higher than that of present-day bombers.

✦ ✦ ✦

THE Corporal E, Army Ordnance ground-to-ground guided missile, is to be mass-produced by the Firestone Tire and Rubber Company.

✦ ✦ ✦

THE Russians are reported to be producing liquid-rocket-powered fighter aircraft having a speed of 1700 mph at 100,000 ft altitude. The pilot lies in a prone position while operating the aircraft.

✦ ✦ ✦

THE British Royal Airforce Establishment has developed a liquid propellant rocket unit, known as the Beta II, to power experimental aircraft models of unconventional design. The self-contained unit will give a thrust of 2500 lb for 40 sec. A steam turbine drives the propellant pumps. The production model of the Beta II is to be produced by Fairey.

Aircraft

CONSOLIDATED Vultee Aircraft Corporation (Convair) has been given a production order to build America's first supersonic delta-wing interceptor for USAF. It is designated F-102, and will be built at Convair's San Diego Division. Much of Convair's delta wing design information was obtained from flight tests of the Air Force's XF-92A, shown in Fig. 4, research interceptor built by Convair in 1948.

Due to their low aerodynamic drag, deltas fly faster than conventional aircraft with equal power. The deltas also experience no aerodynamic disturbance in the transition from subsonic to supersonic flight, that is, no buffeting, or reversal of controls. The larger wing areas of the delta aircraft provide increased lift and also more space for fuel, without resorting to wing-tip tanks. The delta's response to inadvertent wind gusts is said to be much less severe than for more conventional airplanes.

✦ ✦ ✦

FIG. 5 shows an artist's conception of the Ryan Aeronautical Company's jet-propelled pilotless target plane, the Q-2. Less than half the size of a jet fighter, but with comparable performance, the Q-2 will be used for anti-aircraft training and fighter plane interception problems. The Q-2 drones, a result of a joint Air Force-Navy-Army project, are currently being flight tested in New Mexico. During flight, the drones are remotely controlled by a ground operator.

FIG. 5 RYAN Q-2 PILOTLESS DRONE

✦ ✦ ✦

THE Air Force has ordered an undisclosed number of F-100 jet fighters from North American Aviation. No performance data or design configuration of the F-100 has been released, although it is understood that the plane is designed for aerial combat at speeds faster than sound.

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THE world's largest helicopter, the jet-powered XH-17, shown in Fig. 6, built by Howard Hughes Aircraft Company for the USAF, is undergoing flight tests at Culver City. Two modified General Electric turbojet engines supply air through ducts leading up the rotor shaft to afterburners located at the tips of the long rotor blades. The exhaust jets of the afterburners supply the necessary thrust to drive the 137-ft span rotor. The XH-17 is designed for short range moving of heavy military equipment including artillery, tanks, bridge sections, and trucks.

✦ ✦ ✦

THE Navy has awarded the Glenn L. Martin Company a contract to build a high-speed jet-propelled seaplane designated by Martin as the model 275 Sea Master. The new seaplane will be radically different in its concept and design. No design or performance details have been released.

FIG. 7 shows the Army's one-man pulse jet XH-26 in flight. The "jet-jeep," as the XH-26 is known, has a top speed of 80 mph and carries a load of 600 lb or twice its own 300 lb weight. The pulsejet engines mounted at the rotor tips burn gasoline, kerosene, or diesel fuel oil at such a rate that the plane can fly for $1^1/_2$ hr without refueling.

The engines can be started by pressing a button on the cyclic control stick which injects air and fuel into the engines, during which time a small spark plug ignites the fuel and air mixture. The spark plug is then turned off. Thirty seconds after the pilot enters the ship he is airborne. Since the ship has no hydraulic system, no engine lubrication problem, and

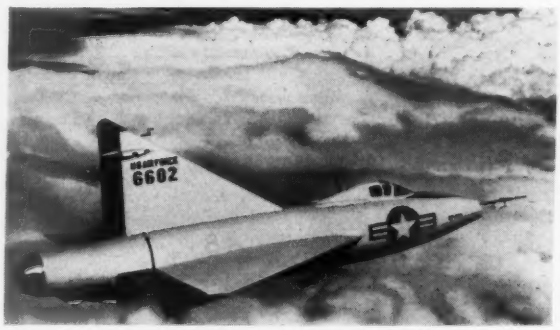

FIG. 4 CONVAIR XF-92A, USAF DELTA-WING RESEARCH AIRCRAFT

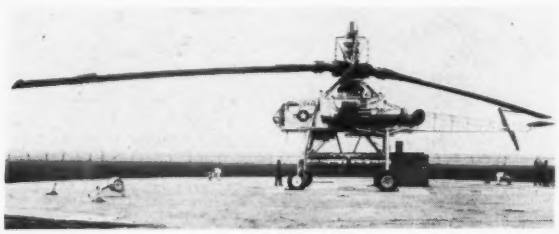

FIG. 6 WORLD'S LARGEST HELICOPTER, HUGHES XH-17

FIG. 7 THE AMERICAN HELICOPTER CO., INC., JET JEEP

FIG. 8 BRITISH BOULTON PAUL P-120, DELTA RESEARCH PLANE

no extensive electrical circuit, the maintenance problems are minor. The engines can operate 50 hr with absolutely no maintenance, and an overhaul can be accomplished in a few minutes since the engine has only one moving part.

The ship is collapsed into a 5 × 5 × 14-foot container which can be dropped by parachute from larger planes. Two men can unpack the helicopter and have it in the air in 20 min.

The tiny tail rotor, driven by belts, is not used as an anti-torque rotor, as no torque is generated in the fuselage with tip-mounted engines. The purpose of the tail rotor is to improve directional control. Failure of the tail rotor will not hamper the pilot except possibly in high winds during precision maneuvers.

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PAN American World Airways, Inc., has ordered three Series III Comets for delivery early in 1956. The new Comet, powered by four Avon 9000-lb thrust turbojet engines, will be half again as large as the present Comet. It is expected that the Series 3 Comet will be able to carry 60 passengers at 500 mph.

✦ ✦ ✦

THE Brazilian Government has signed a contract of more than five million pounds with the Gloster Aircraft Company for 60 "Meteor 8" ground attack fighters and 10 "Meteor 7" trainers. These planes, Brazil's first jets, will constitute the backbone of the Brazilian Air Force.

✦ ✦ ✦

FIG. 8 shows the British Boulton Paul P-120 delta research plane. Powered by a Nene turbojet, the P-120 will be used for aerodynamic research at near sonic speeds. The plane has a span of 33 ft $5^1/_2$ in. and a length of 29 ft $7^1/_2$ in.

✦ ✦ ✦

A NEW Russian medium bomber, known as the Model 150, is said to be making its appearance in the Russian sky. The swept-wing bomber is said to be powered by two Lulkow 11,400-lb thrust turbojet engines. These engines give the Model 150 a maximum speed of about 650 mph and a range of 2250 miles at 45,000 ft. Dr. B. Baade, the well-known German designer, is thought to be in charge of the development group of the 150.

✦ ✦ ✦

THE British RAF has named the new AVRO 698 jet-powered delta bomber, shown in Fig. 9, the Vulcan. It is rumored that four Olympus turbojet engines will power the production models of the Vulcan. The Vulcan is thought to have a wing span of approximately 100 ft and to be the world's fastest bomber.

Turbojet Engines

THE Société Nationale de Constructions Aéronautique du Sud-Ouest (SNCASO) of France has conducted extensive take-off tests of a DC-3 fitted with a Palas (350-lb static thrust) turbojet engine acting as a jet boost take-off unit. The added thrust developed by the Palas increases the climb rate at take-off by 70 fpm, which corresponds to an increase in allowable pay load of 1770 lb. The use of the Palas as a jet assist take-off unit makes it possible for the economical DC-3 to meet ICAO requirements without reducing its payload.

The results of these flight tests may open up a new field for small turbojet units. The noise of the Palas when running is much less disturbing to the passengers than is that of rocket assist take-off unit, and there is no disagreeable exhaust smoke.

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SOLAR Aircraft Company has just delivered its first Mars gas turbine driven auxiliary power plant for airborne use to the Air Force. The basic hand-started gas turbine, weighing

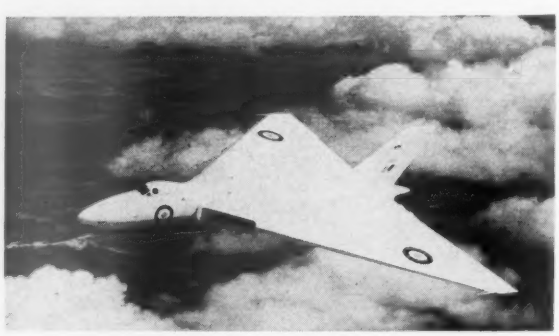

FIG. 9 BRITISH AVRO VULCAN

60 lb, develops 45 hp output at 40,000 rpm. The unit, designed for Air Force cargo transport use, will supply current for the operation of cargo doors and lifts when the aircraft are on the ground.

✦ ✦ ✦

ARMSTRONG Siddeley finds itself in the enviable position of building too good a product. While other jet engine builders are striving to build longer life into their product, Armstrong Siddeley engineers are busy redesigning their Viper, a 1575-lb thrust turbojet, for shorter life. The Viper, used to power-guided missiles and pilotless target aircraft, was supposed to have a maximum life of 10 hr. Current production model Vipers are exceeding the minimum thrust requirements and have a service life of 100 hr.

✦ ✦ ✦

DUE to the increased auxiliary power requirements of jet aircraft, jet engines are running out of available pad space for driving accessories. The front end of the engine is being seriously squeezed. Decreasing compressor hub-to-tip diame-

ter ratios, in order to obtain maximum engine air flow in a given engine, have been a big factor in lessening of pad space. With available pad space down to practically nothing, the only way to accommodate accessories on the engines is to enlarge the nacelles and thereby increase their drag. One solution to this problem is to use auxiliary power plants.

A new pneumatic system for supplying such auxiliary power is being manufactured by the Aircraft Gas Turbine Division of the General Electric Company. The unit, designed to supply either electric or hydraulic power, is driven by turbine supplied with air from the compressor of the main turbojet engine. The 60-kva electric power unit is driven by a single-stage variable-area axial flow turbine, whereas the hydraulic unit supplying oil at 3000 psia is driven by a high-speed radial inflow turbine.

New Facilities

A NEW combustion laboratory and a water filtering plant are being added to the facilities of the Army Ordnance Corp's Malta missile test station at a cost of $440,000.

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THE extensive equipment required for the testing of ramjet engines is shown in Figs. 10 and 11. This laboratory is a joint project of the U. S. Navy and United Aircraft Corporation.

✦ ✦ ✦

McDONNELL Aircraft Corporation is currently engaged in an extensive expansion program at Lambert Field, St. Louis, Mo. Part of this program includes a million-dollar propulsion laboratory completely equipped for testing jet engines under simulated flight conditions, and a million-dollar low-speed wind tunnel. A power plant capable of developing approximately 3000 hp will be used to drive either of two

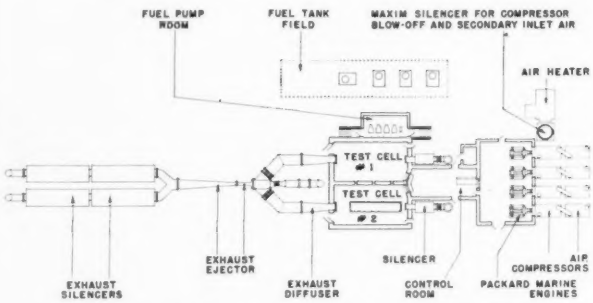

FIG. 10 LAYOUT OF USN-UAC RAMJET TEST LABORATORY

compressors serving the two test cells of the propulsion laboratory. These units will help further studies of ramjet and pressurejet power plants.

Rocket Carries Mammals to 200,000 Feet

THE Air Force has disclosed that mammals were recovered alive and unharmed recently after being fired to approximately 200,000 ft in the upper atmosphere in an Aerobee rocket. This flight provided information on the reactions of mammals under conditions of zero gravity and extreme altitude. Two monkeys and two mice, the mammals involved in this flight, were recovered alive and in good health after the test at Holloman Air Force Base, Alamogordo, N. Mex. From the knowledge gained by these experiments, the Air Research and Development Command has concluded that it is possible for a mammal to function within the range of normalcy during rocket flight.

In order to study their reactions in detail, it was necessary to perfect telemetering and photographic equipment to record

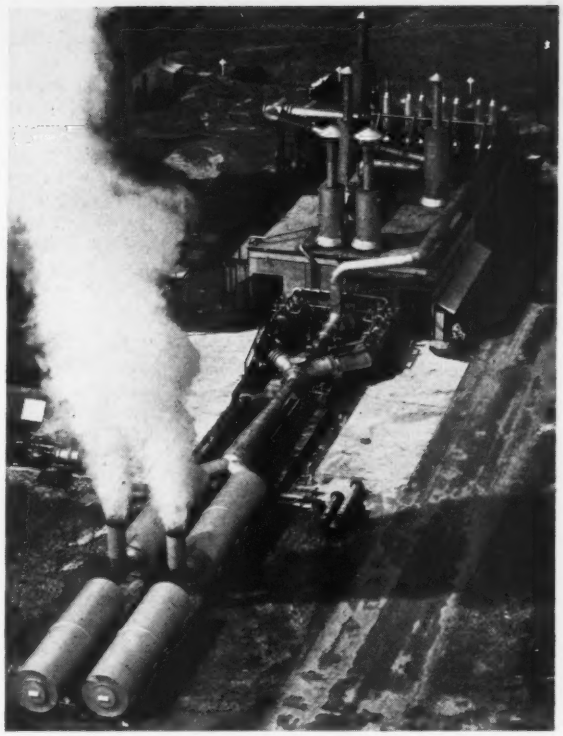

FIG. 11 VIEW OF USN-UAC RAMJET TEST LABORATORY

the activities of the subjects during the high acceleration of take-off, the weightlessness (zero gravity) at the crest of the trajectory, and the opening shocks of descent and recovery by parachute. The monkeys and mice experienced no unusual effects from the flight, although they were subjected to a brief initial acceleration of about 15 g, lasting less than one second, and a longer force of 3 to 4 g, lasting for 45 seconds. The monkeys were anesthetized to prevent their disturbing the instrumentation necessary to record their physiological reactions. During this rocket flight and the periods of zero gravity, the mouse in the smooth drum, floating free, appeared to have completely lost his senses of direction and orientation and was unable to direct his movements normally. However, the mouse in the drum containing a small shelf was able to cling to it, orient himself, command his body at will, and did not float in space. These reactions, plus several human experiments in jet fighter aircraft, have indicated that a man, properly secured in an aircraft, can function normally during brief periods of zero gravity and perform any operations necessary in piloting an aircraft.

These research tests have given added emphasis to Air Force belief that man will be able to withstand the unusual forces expected in rocket flight to the outer atmosphere. It is corroborated from these experiments that little or no loss of physical or mental powers would be experienced in the so-called "zero gravity" or weightless state encountered during brief rocket flights. However, the official Air Force report on these experiments states: "Physiological results obtained with monkeys and mice can only be applied with caution to men."

Upper Air Research

A GROUP of scientists and technicians from the United States Air Force's Cambridge Research Center, augmented by scientific personnel from the Universities of Michigan, Denver, and Connecticut, and the Harvard College Observatory, have carried out a series of co-ordinated scientific investigations of the upper atmosphere at the Holloman Air

Development Center. Raymond A. Minzner of the Geophysics Research Directorate, Cambridge Research Center, co-ordinated the performance of four independent experiments with rocket, ground explosions of TNT, meteors, and searchlight penetration of the night skies to determine temperatures and winds up to 70 miles above the earth's surface.

The project, part of the Air Research and Development Command's continuing study of the upper atmosphere, was entitled "T-Day," or Temperature Day, and was set to coincide with a period of the year in which large numbers of meteors are expected in the New Mexico sky. These small metallic particles invade the earth's atmosphere where friction set up by air molecules causes the meteors to glow brightly and gradually lose their speed. In this experiment, special photographic devices were used to measure the rate of the deceleration and change in brightness of meteors. Such measurements provide indication of the atmospheric density which then can be interpreted in terms of temperature. Study of the motion or drift of the various faintly luminous remains of the meteor trains provided another means of measuring winds 50 miles above the earth.

The rocket phase of T-Day was carried out by scientists of the University of Michigan under the direction of Nelson W. Spencer of Ann Arbor. Since direct temperature measurements could not be made from the rocket because of its high velocity and the thinness of the atmosphere at high altitude, special pressure gages to determine densities were installed on the rocket surface. Density readings obtained by these gages permitted interpretation in terms of temperature since there is a direct relationship between the density of the air and its temperature. From these periodic measurements of the rapid velocity and orientation it was possible to calculate the force of the wind up to the peak of the rapid projectory usually 70 miles up.

The sonic phase of the co-ordinated project, the determination of upper atmosphere temperatures from the refraction of sound waves generated by TNT explosions, covered a wide area of New Mexico and west Texas. This method of determining high altitude temperatures makes use of the principle that under certain conditions of temperature distribution in the atmosphere, the sound of an explosion may be heard at points hundreds of miles away while areas nearer the explosion record no sound. Six recording stations throughout New Mexico and west Texas were tuned to receive the very low frequency sounds which were propelled skyward at the scene of the explosion in the White Sands area, and then refracted downward along paths determined by the atmospheric temperature distribution to the listening devices hundreds of miles away.

The fourth experiment was the searchlight technique. Two 60-in. antiaircraft searchlights were set up on adjacent mountain tops. Only one, however, transmitted the normal high intensity beam skyward. The other was equipped with an extremely sensitive photomultiplier which could receive and magnify the most minute intensity of light. The light beam was flashed on and off at a fixed frequency to which the light receiver was tuned to respond. In this way all extraneous light such as moonlight, starlight, and airglow was eliminated. The intensity of the light received from the different altitudes depended on the amount of scattering of light by the atmosphere at that altitude. Light scattering depends on the density of the air, the denser the air the greater the scattering. Densities could, therefore, be determined by the experiment and converted to temperature values.

Scholarship

THE International Organization of Executive and Professional Women has established an annual scholarship in honor of Amelia Earhart. The scholarship in the field of aeronautical engineering will be awarded to a woman who holds a bachelor's degree and who has been recommended for fine character and high ability. The scholarship of $1200 will be awarded each year for graduate study in aeronautical engineering at any approved engineering school. Those interested should write to Miss J. Winifred Hughes, Syracuse University.

Jet Speed Boats

TWO jet-propelled speed boats of radically different design have been built in England. The Crusader was built for the late John Cobb, and the White Hawk was built for Frank Hanning-Lee. The Crusader, in which Cobb met his death, had a long thin cigarlike frame riding on two outboard floats. Aircraftlike in its design and construction, the Crusader was powered by a 5000-lb thrust Ghost turbojet engine. A one-sixth scale model, powered by one RAF Farnborough solid rocket delivering a 30-lb thrust for 20 seconds, attained a speed of 97.5 mph. The Crusader reached an unofficial speed of 206.89 mph. The White Hawk, a similar craft, is currently trying to better that mark.

Guggenheim Jet Propulsion Fellowships Available at Princeton and CalTech

DANIEL and Florence Guggenheim Jet Propulsion Fellowships will be awarded for graduate study at Princeton University, Princeton, N. J., and the California Institute of Technology, Pasadena, Calif., at the Jet Propulsion Centers established in 1948 by the Daniel and Florence Guggenheim Foundation. From 9 to 12 Fellowship grants including renewals, totaling $18,000 in stipends, are available at each institution. Each Fellowship carries a stipend ranging from $1000 to $2000 annually, plus tuition, for study toward advanced degrees.

The purpose of these Fellowships is to select and train outstanding men for basic research and for leadership in the development of rockets and jet propulsion, with special emphasis on peacetime uses. The Fellowships are open to qualified college graduates with suitable engineering or scientific preparation. Candidates must have outstanding technical ability, demonstrated leadership qualities, and deep interest in rockets and jet propulsion.

Applications must be received by March 1, 1953, and will be acted upon by April 1. Candidates will be notified promptly. Applications and descriptive booklets may be obtained from either institution.

✦ ✦ ✦

ACKNOWLEDGMENT: The description of the Maxim Silencer which appeared in the November-December, 1952, issue of the JOURNAL, pages 347–348, was taken from *Shell Aviation News* by permission.

Some Experiments on Flow Separation in Rocket Nozzles

(*Continued from page 32*)

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American Rocket Society News

H. K. WILGUS, *Associate Editor*

The 1952 ARS Annual Convention: A Technical Summary

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Introduction

THE American Rocket Society's 7th Annual Convention, held at the Hotel McAlpin in New York City from December 3 to December 5, 1952, reflected the Society's rapid and expansive growth with the presentation of a record number of nineteen papers. Such fascinatingly imaginative topics as the physiological implications of the Martian atmosphere and problems of survival in space were program companions with papers reflecting the serious and pressing problems of the jet propulsion industry today, and dealing with such topics as combustion instability in liquid propellant rocket motors and ignition problems of common bipropellant combinations. The luncheon and dinner speakers also followed in this contrasting vein. Dr. W. von Braun extolled at the Friday luncheon the exciting concept of a satellite vehicle as an instrument of world peace; whereas Lt. Gen. L. C. Craigie, USAF, in his Honors Night Dinner address, pointed to the role of rocket power as a key tool in the Air Force's arsenal and stressed the need for research and development on present-day problems in order to assure security by the attainment of unquestioned superiority in the application of rocket power to aircraft and missiles.

The scope of the papers is a verification of the tremendous potential of the Society as a focal point for engineers and scientists in many different fields whose combined energies are essential to the fruitful research and development of rocket and jet propulsion devices. Progress is coincident with an understanding of the many widely different problems such as, for example, elements of combustion with its related chemical and gas dynamic factors, or guidance and control with its electronic implications. With such opportunities for expansive and fruitful extensions, it is rather unfortunate that an excessive number of the program items were merely elementary and extensive descriptive presentations of well-known material, rather than scientific or engineering papers. In some cases, these were responsible for the serious lack of discussion time for the significant and controversial papers. It is sincerely felt that greater emphasis on discussions, together with panel-type meetings on key subjects, would greatly enhance the effectiveness of such a convention.

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[4] National Science Foundation Fellow, Jet Propulsion Program.

First Session

E. H. Hull of the General Electric Company was the presiding chairman for the first session, and was assisted by R. J. Thompson of the M. W. Kellogg Company. The first paper of the afternoon dealt with the serious problem of combustion instability in liquid propellant rockets engines and was presented in the absence of the authors, R. S. Levine and R. V. Lawhead, by G. P. Sutton of North American Aviation, Inc. The paper classified combustion instability types into four categories. The first two are low frequency in nature and are due to the time lag of the oscillations in the feed system either directly induced by chamber pressure oscillations or through the instability of the feed control servos. The third type is high frequency in nature and is referred to as acoustical. It was concluded that the critical mode producing hot spots in rocket motors is a transversal acoustical mode. The fourth type of instability was said to be due to the inability of the combustion process to maintain itself, and this was cited as an explanation for observed frequencies which could not be classified under any of the three preceding types. The basic mechanism of self-excitation is, of course, essentially the same for all the first three types; mainly, a time lag between the pressure oscillation and the resulting oscillation of the rate of generation of combustion products. Although various types of oscillations are classified as acoustical, this does not necessarily mean that the mechanism inducting the resonance is similar in all cases. Frequencies close to the acoustic value are obtained simply because the speed of wave propagation in the slowly moving medium is nearly acoustical.

The second paper of the afternoon dealt with a simplified combustion analysis system and was prepared by R. Neumann, D. Dembrow, W. Berl, and R. Prescott, of the Applied Physics Laboratory of Johns Hopkins University. The paper covered a scheme for analyzing combustion gas composition in the absence of dissociation reactions. By comparing the thermal conductivity of a standard gas and the specific gas sample, the content of carbon dioxide in the sample is determined continuously. Three measurements are made on the dehydrated sample. The total carbon content is measured by determining total CO_2 present after complete oxidation of the sample. The fraction of carbon in the form of CO_2 is obtained by the difference of the total carbon content and the carbon content of the sample after removal of CO_2 by Ascarite. The carbon monoxide content is determined after the removal of the CO_2 by Ascarite and unburned fuel by activated carbon by oxidizing the remaining gas to CO_2 and measuring it in the thermal conductivity cell. The obvious limitations of the method as applied to rocket motors in which extension dissociation takes place, and to the determination of the temperature under nonadiabatic conditions were pointed out in the discussions which followed the presentation.

The final paper of the afternoon also dealt with combustion studies in liquid rocket motors and was presented by K. Berman and S. H. Cheney of General Electric Company. The paper presented additional results to those made available at the sixth Annual Convention of the Society. The method involves the use of a slit-window motor and strip camera to obtain information about instability phenomena in rocket motors. The observed high frequency oscillations are arbitrarily divided into two types—the shock type with large amplitudes, and the sinusoidal type with significantly smaller amplitudes. It was shown that the appearance of the shock type is always preceded by the sinusoidal type, and a record of the process of transition was presented. Some evidence was also offered to indicate that rocket motors with longer combustion chambers and larger values for the converging angle of the nozzle, but with the same chamber and throat area, are more unstable. For given geometrical configurations, the system is destabilized by lowering combustion chamber pressure through the decrease of mass flow. The rough burning results in mechanical shock and large heat transfer rates across the wall, as has been previously observed. A lively discussion period followed the presentation of the paper and

included written discussions by S. Datner of the Aerojet Engineering Corporation, and S. I. Cheng of Princeton University. Mr. Datner questioned the use of linearized theory approach to instability problems which are so definitely nonlinear in character. On the other hand, Dr. Cheng pointed out that the definite presence of the transition from the sinusoidal type to the shock type with increasing amplitude, thus defining the onset of instability, is exactly what one hopes to predict by linearized theory.

Second Session

The second session of the convention was presided over by the President and Vice-President Elect of the Society, F. C. Durant, III, and A. G. Haley, respectively. The first paper of the session was presented by H. Strughold of the USAF School of Aviation Medicine at Randolph Field, Texas, and dealt with the atmospheres of Earth and Mars in the light of recent physiological concepts. Dr. Strughold discussed the present-day concept of the classification of the terrestrial atmosphere from the biological and technical point of view. This concept considers a transition zone between the atmosphere and free space, with the transition zone being characterized by the fact that the various functions which the atmosphere has for man and aircraft cease at various altitudes, and those factors typical of space come into play one by one, finally dominating the field. The paper primarily treated those functions of the atmosphere resulting from its oxygen and barometric pressure. Dr. Strughold pictured the Martian atmosphere as corresponding in many ways to that of the Earth's atmosphere above an altitude of 56,000 ft. The conclusion was clear that the Martian atmosphere as physical environment is completely unsuitable for high living beings as we know them, but there appears a likelihood that lower organisms might well exist.

The second paper of the morning by F. Haber, also of the USAF School of Aviation Medicine at Randolph Field, discussed the problem of the escape and survival in space travel. Dr. Haber broke up the problem into three categories: First, those accidents at a very great distance from Earth; second, those outside of the Earth's atmosphere, but closer to the Earth, such as in the case of a satellite missile; and third, accidents occurring between the surface of Earth and borders of the atmosphere. The chances for survival of a body falling from an extreme altitude back to Earth were shown to be nonexistent, despite the fact that the terminal velocity at sea level is relatively low, namely, around 100 mph. The temperatures and accelerations encountered during the drop would nullify any possibilities of survival. In the first two cases, survival is remotely possible, provided means are available for communication and prompt location, and provided means of survival away from the main space ship for a reasonable period of time can be made possible, and provided further that he can be reached promptly by a rescue ship.

K. Ehricke, of the Guided Missiles Development Group at Redstone Arsenal, delivered the third paper of the morning on the question of a method of using small orbital carriers for establishing satellites. This interesting paper discussed the use of a series of orbital carriers as a means for establishing and maintaining satellite vehicles. The pay load of these carriers would be transferred from the auxiliary orbit just above the atmosphere to the orbit of the satellite by means of space ferries. Considerable gains in efficiency and economy could be effected by such a scheme. Dr. Ehricke made the very interesting point that a satellite vehicle designed for observation of the Earth's surface would be highly unsuitable as a launching platform for interplanetary travel. This is in view of the fact that for observational purposes a most suitable orbit would be one inclined to the ecliptic plane, whereas for interplanetary travel an equatorial orbit is the most desirable one and the transition would involve large expenditures of additional energy. To leave from an inclined orbit would require a sensitive adjustment of conditions that would make interplanetary travel a very rare event. Dr. Ehricke presented for illustrative purposes a numerical example considering the altitude of the large satellite to be of the order of 1000 miles. The feasibility of establishing an auxiliary orbit of pay-load transfer at altitudes of the order of 130–150 miles was shown. Various satellite ships, each progressing in an orbit designed for its specific mission, could be supplied by orbital carriers in this way. The economy of such a scheme was stressed.

In the concluding paper of the session, G. P. Sutton of North American Aviation, Inc., sought to paint a picture of rocket developments behind the Iron Curtain on the basis of such information as could be obtained in the open literature and also interpreted from information appearing therein. It was concluded that the rocket industry behind the Iron Curtain must be making substantial progress.

Third Session

C. F. Warner of Purdue University presided over the afternoon session, assisted by R. L. Duncan of the Power Branch of the Office of Naval Research. In the opening paper, M. Harned of Marquardt Aircraft Company described the applicability of the ramjet as a power plant for aircraft propulsion. A general review of the performance, reliability, cost, installation requirements, serviceability, and applications was presented. Comparisons with other power plants were drawn. The ramjet's greatest potential was again shown to be in the high Mach number range from 2 to 4. The ramjet with a rocket booster was suggested as an ideal power plant for efficient supersonic pilotless aircraft propulsion. Certain limited subsonic applications were also discussed.

As the second presentation of the afternoon, W. C. Schaffer, of the Wright Aeronautical Corporation, spoke on the use of analog computers for turboprop control investigations. His narration dealt with time savings obtained by the use of computers; flexibility that can be obtained by utilization of analog components; and the use of the analog for training control engineers. A slide of a computer record and photographs of standard computers completed the presentation.

The third paper, offered by E. F. Lype, Armour Research Foundation, dealt with the calculation of the pressure in the motor of a gun-launched solid propellant rocket during the period the rocket motor is in the gun tube. For design calculations, a knowledge of the pressure in the rocket motor is required. The differential equations for pressure and temperature of the gases in the motor were derived from conservation relations, the burning law for solid propellants, the orifice flow equation, and the equation of state. No solutions or experimental data were presented, and no conclusions were offered.

The concluding paper of the session, presented by R. P. Haviland of the General Electric Company of New York, dealt with telemetering instrumentation for rocket flight tests. This paper described in elementary fashion a limited number of simple instruments used in flight testing and designed to operate with the Hermes telemetering system. Basic design factors and operating limits dictated by the system were given. Acceleration, temperature, position, velocity, and two types of pressure sensors were discussed, and some mention was made of monitors and an isolator.

Fourth Session

The first session of the final day's program was under the chairmanship of M. B. Schilling of Redstone Arsenal, with R. B. Foster of Bell Aircraft Corporation as vice-chairman. An evaluation of competing rocket power plant components for two-stage long range vehicles was presented by A. L. Feldman of Consolidated Vultee Aircraft Corporation. The basis for comparison concerned the effect that small changes in the weight and operating efficiency of rocket power-plant components have on the amount of propellant required to power a two-stage missile a given distance with the given pay load. Two similar missiles were compared, identical in all respects except for the component under consideration. The criterion for constant range was approximated by the relation that $I \ln M_f/M_e =$ constant, where I is the average effective specific impulse for the two stages, and M_f/M_e is the mass ratio. The expression for the change in propellant weight was expressed as a quadratic equation, whose roots depended upon such parameters as the component weight change, specific impulse ratio for the two missiles, etc. Curves were shown for a simplified form of this exchange function, and several illustrative examples were given. It was concluded that the results presented must be coupled with the knowledge of cost, availability, reliability, etc., before a final judgment could be made.

The effect of variation in propellant density on rocket performance was an interesting treatment of the possible improvement in performance of an ideal rocket resulting from the replacement of portions of the rocket fuel by high density additives. The study was undertaken by J. Lorell and A. Hibbs of the Jet Pro-

pulsion Laboratory, California Institute of Technology. The paper was specifically concerned with maximizing the quantity U_f / U_f^*, where U_f is the burnout velocity, and U_f^* is the burnout velocity with zero additive. Two cases were considered: First, the case where the proportions of fuel and additive were held constant during flight; and second, the case where the mixture ratio was allowed to vary during the burning time. The primary assumption imposed on the analysis was that the rocket-empty mass and propellent volume were the same for all cases considered. The results for the first case showed that the additive fuel/density ratio should be as large as possible and, for an inert additive, the ratio must be greater than two for any improvement at all. The optimum mixture ratio is expressed in terms of the density ratio. A more refined analysis was made for the case of variable mixture ratio using methods of the variational calculus. The results in this case show in general that improved performance is obtained by programming the mixture ratio so that the high density propellant is consumed during the early part of the trajectory. In the ensuing discussion, Dr. Yachter cited his own previous investigation of the same problem with the additional specification of equal burning times, with the result that the improvement was negligible except for density ratios greater than four.

C. C. Ross, of the Aerojet Engineering Corporation, presented the third paper of the afternoon in place of J. E. Zimmerman, Wright Air Development Center, who was unable to deliver the paper in person. Mr. Zimmerman's paper dealt with the effects of pump performance on liquid propellant rocket design. Because of the fact that 25 per cent or more of the total rocket engine weight must be allocated to fuel pump equipment, the author stresses the importance of a study of pump system parameters in general and the unique properties of turbopumps in particular. The study is based on the assumption that the critical variables in turbopump design are the pump and installation weights and their effects on rocket range. Using the pump parameters of rotational speed and net positive suction head, a graphical presentation was made to show the relationship between these important design quantities and also their relation with pump weight, turbine weight, and system weight. Other factors, such as pump discharge pressure and efficiency, were also discussed. Finally, the importance of minimizing the pump weight installation was graphically demonstrated by a curve showing the ratio of the turbopump assembly weight to total rocket weight and its effect on ballistic and Breguet trajectory ranges.

The concluding paper of the fourth session was read by Lt. George W. Meckert, Jr., of Edwards Air Force Base, Edwards, Calif. Largely descriptive in nature, the paper dealt with the methods of handling and analyzing hydrogen peroxide. Testing procedures used in quality control were enumerated, and factors concerning stability testing were also listed. In conclusion, the author listed various recommendations for improvement of servicing systems, safety clothing, etc.

Fifth Session

R. C. Stiff of the Aerojet Engineering Corporation, and R. Youngquist of Reaction Motors, were the presiding officers for the fifth and final session of the convention. The first paper of the session by K. C. Halliday of Bendix Aviation, was an extensive discourse on the subject of ignition of fuel with nitric acid. The paper narrated six years' experience of the author's laboratory with this widely known oxidizer. Physical and chemical properties and hypothetical reaction schemes involving nitric acid were discussed. Hypergolic and nonhypergolic systems involving nitric acid as the oxidizer were also treated, and speculative remarks were offered on such topics as the atomization of the propellants, combustion limits, mixing mechanisms, etc.

As the next item on the program, R. F. Potter of the Bell Aircraft Corporation, presented an interesting analysis of the effect of chemical reactions upon predicted performance of rocket motors. The paper presented a general analytical method for dealing with a gaseous flow system in which chemical reactions are occurring. The author showed the modified form of the steady fluid-flow equations resulting from chemical reaction, and derived an expression for value of the velocity of sound in a medium in which chemical reaction is proceeding. It was illustrated that values for the sonic velocity at the throat could be obtained which were intermediate between those that one would obtain by the assumption of acoustic wave propagation as an isothermal phenomena or as an adiabatic phenomena. The effect on throat temperature and density in the case of a reacting gas mixture was also noted. It appeared that the method of Dr. Potter offered no advantage over existing methods of handling the problem.

The third paper of the afternoon session was a concise description of the unique characteristics and advantages of the nitric-acid-ammonia propellant system for rockets. The author, R. J. Thompson of M. W. Kellogg Company, stressed the fact that for many applications, such criteria as safety, reliability, simplicity, practical utility, and cost, frequently allow the designer a very limited number of possible propellant combinations. In particular, the oxidizer which best meets the requirements demanded by quantity production is generally regarded today as being nitric acid. The fuels usually considered in combination with nitric acid, such as aniline, hydrazine, gasoline, etc., are shown to be inferior to ammonia in many respects. The specific impulse of the WFNA - liquid-ammonia system compares favorably with the other nitric acid systems, and the flame temperature is considerably lower. Test results indicating ease of handling, wide operational limits, safety, etc., were noted, as well as the technique of catalytic starting.

The final paper of the convention concerned a modified sodium line reversal technique for the measurement of combustion temperature in rocket engines, and was presented by M. F. Heidmann and R. J. Priem of the NACA Lewis Flight Propulsion Laboratory. It was noted that the variations of flame temperature in the rocket motor afford one of the best methods for measuring the extent of reaction and hence, efficiency of the particular motor. The flame temperatures are calculated from variations in radiation intensity produced by intermittently transmitting light from a tungsten lamp through the combustion flame. The determination of axial flame temperature profiles with an average deviation of about 50 F was indicated.

This paper brought to a close the Seventh Annual Convention of the American Rocket Society, and it is only fitting to acknowledge the work of the many persons whose combined efforts made possible the most extensive technical program in the history of the Society.

Highest Registration for Seventh Annual Convention of American Rocket Society

WITH a registration of more than 1000 members and guests, the ARS Seventh Annual Convention got under way at the McAlpin Hotel, New York, N. Y., on Wednesday, Dec. 3, 1952, and continued through Friday, Dec. 5. Held in conjunction with the Annual Meeting of The American Society of Mechanical Engineers at the nearby Statler Hotel, the broad program at both Meetings of technical sessions, papers and addresses, luncheons and dinners attracted a total registration of 7000—setting a new high in attendance. All of the events were attended to capacity, and some of the technical sessions were filled to overflowing.

Annual Business Meeting

The ARS Annual Convention opened on Wednesday morning with the Annual Business Meeting at which 40 members were present. Mr. C. W. Chillson, ARS president, presided, and reports of the year's activities were submitted by the General Counsel and Chairmen of the standing Committees, the Ad Hoc Space Flight Committee, and the Nominating Committee. The following officers and Directors were elected for the year 1953: *President*, F. C. Durant III; *Vice-President*, Andrew G. Haley; *Directors* (for a term of three years), Noah S. Davis, Jr., Kurt Berman, and Roy Healy. A discussion of nominating procedures to be followed in 1953 followed the presentation of the reports. The results of the Business Meeting will be included in the Annual Report to the members.

ARS Section Luncheon

On Wedensday noon the second Section Luncheon was held for delegates and officers from all established Sections and

those in the process of formation. The Section Luncheon at the Annual Convention had been initiated the previous year for the purpose of hearing reports from the Sections on their year's activities.

Thirty-one members attended, and the following Sections and Groups were represented: New York, Washington-Baltimore, Indiana, New Mexico-West Texas, Northeastern New York, Princeton group of the New York Section, Fairleigh Dickinson Student Section, and the newly forming San Francisco and Niagara Frontier Sections.

Mr. F. C. Durant, III, retiring ARS vice-president, gave a report on the Third International Astronautics Federation Congress which had been held in Stuttgart, Germany, Sept. 1–6, 1952.

Mr. Lee Bregenzer, retiring president of the New York Section, reported that eight meetings had been held during the year including a special one when A. C. Clarke, chairman of the British Interplanetary Society, came to this country unexpectedly. Mr. Bregenzer emphasized the fact that the New York Section is making a strong effort to present entertaining as well as educational programs. He stated that the Section had come in close contact with various student groups, and he expressed the opinion that such groups should be encouraged to participate in ARS activities.

Mr. Edward E. Francisco, Jr., secretary-treasurer of the New Mexico-West Texas Section, said that due to the increasing interest in ARS activities, the Section had been re-energized during the past few months. He reported on several recent outstanding Section meetings that had attracted attention, and stated that because of the interest expressed by students at New Mexico A. and M. College, there was every indication an active section would soon be organized at White Sands.

Mr. J. P. Layton, vice-chairman of the Princeton group of the New York Section, reported on the charter meeting held on November 25, 1952, of this newly formed group. The meeting brought together 72 members and visitors and was highly successful.

Mr. F. M. Cooper, president of the Northeastern New York Section, stated that the Section plans another annual meeting in May. The Section, he said, had a special problem in that one of its main objectives had been experimental work, whereas the ARS General Counsel had ruled that experiments could not be carried on by Sections under the jurisdiction of the ARS because of the possible liability of the Society in case of accident. He reported that this program is being replaced by discussions of interesting topics and that the Section would certainly continue to be active.

Mr. William Sprattling, of the Niagara Frontier Rocket Society, reported that this Society is giving serious consideration to affiliation with the ARS, to be known as the Niagara Frontier Section. Mr. Kurt R. Stehling, also of that group, reported that the Toronto Rocket Society is interested in joining with the Niagara Frontier group as an affiliate of the ARS.

Mr. Delbert E. Robison, president of the Indiana Section, reported on their Annual Banquet at which the guest speaker was Dr. Ralph E. Gibson, director, Applied Physics Laboratory, Johns Hopkins University. Mr. Robison stated that the special problem of the Indiana Section was, of course, one of student graduation which resulted in new members and officers each year. He said that interest in the Society seems to remain strong and that future meetings are planned.

Mr. William A. Webb, incoming president of the Washington-Baltimore Section, reviewed the activities of that Section's first year of existence. He reported that the membership has increased from 20 to 160 and that continued growth is certain. He said the main problem was the distance between Washington and Baltimore and the difficulty of co-ordinating meetings. The establishment of two separate Sections, he stated, might solve the situation.

ARS Honors Night Dinner

The high light of the Convention was the Honors Night Dinner held in the Ballroom on Thursday, Dec. 4. The Dinner, at which 262 members and guests were present, was devoted to the presentation of awards and announcement of newly elected Fellows and officers, and an address by the guest speaker, Lt. Gen. Laurence C. Craigie, Deputy Chief of Staff for Development of the Air Force. The ARS was also honored by the presence of S. Paul Johnston, director, Institute of the Aeronautical Sciences; John A. C. Warner, secretary and general manager, Society of Automotive Engineers; Harry F. Guggenheim of the Daniel and Florence Guggenheim Foundation; R. J. S. Pigott, retiring president of the ASME; and Major A. P. de Seversky, noted aeronautical engineer.

Fellowships and Awards Presented

In a short ceremony, Raymond W. Young, chairman of the ARS 1952 Awards Committee, introduced the following men elected to Fellow membership in the ARS for their contribution to the advancement of rocket science and their service to the Society: John Sloop, of the NACA Lewis Flight Propulsion Laboratory; William L. Gore, of the Aerojet Engineering Corporation; Roy Marquardt, of the Marquardt Aircraft Corporation; Wernher von Braun, U. S. Army Ordnance Corps, Redstone Arsenal; and Weldon Worth, of the Wright-Patterson Air Force Base.

Then followed the presentation of awards to men who have made significant contributions to rocket and jet propulsion research.

The ARS Student Award was presented by Raymond W. Young to R. W. Foster, Purdue University, for his paper, "The Theoretical Design of a Rocket Engine Utilizing Uranium 235."

The G. Edward Pendray Award was presented by Dr. Pendray to Dr. Maurice J. Zucrow, Purdue University, for his outstanding book, "Jet Propulsion and Gas Turbines"; for his other major contributions to the technical literature of rockets and jet propulsion; and for his unusual talents as a teacher.

The C. N. Hickman Award was presented by Raymond W. Young, in the absence of Dr. Hickman, to Dr. A. L. Antonio of Aerojet Engineering Corporation, for his aggressive leadership in building an outstanding research and development organization in the field of solid propellant rockets; and for the development of advanced types of solid propellant rockets for specific guided missile and assist take-off applications.

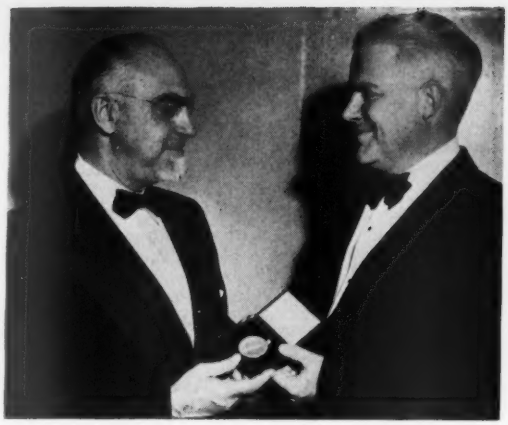
Mrs. Robert H. Goddard, who was unable to be present, requested that Dr. Pendray present the Robert H. Goddard Memorial Award to Dr. R. W. Porter, General Electric Company, for his notable contributions to Project Hermes through his indomitable drive and outstanding technical ability, both as individual and as a group leader, in the analysis, development, and testing of liquid propellant rocket power plants.

Gen. Craigie Says Enemies Are Not on Moon or Another Planet

The climax of the Honors Night Dinner was the address by Lt. Gen. Laurence C.

AT THE HONORS NIGHT DINNER OF THE ARS SEVENTH ANNUAL CONVENTION, MCALPIN HOTEL, NEW YORK, N. Y., DEC. 4, 1952

Left to right: S. Paul Johnston, director, Institute of the Aeronautical Sciences; C. W. Chillson, retiring president, ARS; Lt. Gen. Laurence C. Craigie, guest speaker; and A. P. de Seversky, noted aeronautical engineer.



R. W. PORTER (*right*) OF THE GENERAL ELECTRIC COMPANY, RECEIVES THE ROBERT H. GODDARD AWARD FROM G. EDWARD PENDRAY, AT THE ARS HONORS NIGHT DINNER

DR. A. L. ANTONIO (*left*) OF AEROJET ENGINEERING CORPORATION, RECEIVING THE C. N. HICKMAN AWARD FROM RAYMOND YOUNG, AT THE ARS HONORS NIGHT DINNER

Craigie, Deputy Chief of Staff for Development of the Air Force, who spoke on "The Practical Translation of Rocket Power to Air Power." Gen. Craigie urged the assembled scientists to lay aside temporarily their efforts to conquer space and exercise every means in their power to the solution of the many pressing and immediate problems in rocket development. Our enemies as we know them, Gen. Craigie said, are not located on another planet or on the moon.

The speaker reviewed the science of rockets, pointing out that for several hundred years the rocket propulsion device had been applied intermittently as a military weapon. However, he said, it had not been universally applied and recognized as a powerful component of air and ground weapons until the past decade. He told of the rocket-powered V-2 used by the Germans in World War II, and how later the first manned flight by the X-1 through the sonic barrier was made possible, adding that one could not mention modern rocketry without acknowledging the importance of the Bazooka.

Those scientists who are engaged in thinking and planning for future rocket development, Gen. Craigie said in conclusion, should strive to maintain a suitable division of their energies between thought of space conquest and solution of immediate problems.

Von Braun Speaks on Space Ships at ARS Convention Luncheon

On Friday, Dec. 5, 287 members and guests attended the ARS Luncheon to here Wernher von Braun, technical director, Guided Missile Development Group, Redstone Arsenal, Huntsville, Ala., discuss "Space Superiority, a New Concept for the preservation of World Peace."

F. C. Durant III, incoming president of the ARS, presented the guest speaker, Wernher von Braun, outlining briefly Dr. von Braun's background in rocket science—his work with Prof. Hermann Oberth, with the German experimental program in liquid propellant rockets, and later at Peenemunde where he headed the V-2 program, finally being brought to the United States in 1945.

Dr. von Braun's address was seen to be a reply to the remarks of Gen. Craigie made at the Honors Night Dinner the previous evening. He was not recommending, he said, to go off "half cocked" on making trips to the moon as soon as possible. The important thing, he insisted, is to stop arguments and debates and start thinking and planning about space flight as a military and scientific concept. What is necessary is to create a powerful deterrent to Russian military ambitions. This deterrent, he said, would be a satellite station which could also be used as a missile launching platform against which there could not be effective countermeasures. Once in place, the first space station could prevent the establishment of any other station.

R. W. FOSTER (*left*), PURDUE UNIVERSITY, RECEIVES THE ARS 1952 STUDENT AWARD FROM RAYMOND YOUNG, CHAIRMAN, ARS AWARDS COMMITTEE, AT THE ARS HONORS NIGHT DINNER

G. EDWARD PENDRAY (*left*) OF THE ARS BOARD OF DIRECTORS, PRESENTS THE G. EDWARD PENDRAY AWARD TO MAURICE J. ZUCROW, PURDUE UNIVERSITY, AT THE ARS HONORS NIGHT DINNER

Tombaugh Discusses Life on Other Planets at New Mexico-West Texas Section

MEETING in the Branigan Library Auditorium, Las Cruces, N. Mex., on Oct. 30, 1952, the ARS New Mexico-West Texas Section heard Clyde W. Tombaugh discuss the probabilities of extraterrestrial life. Mr. Tombaugh, now with the Flight Determination Laboratory, White Sands Proving Ground, was a former staff member of the Lowell Observatory, Flagstaff, Ariz. While there he climaxed years of work and study by discovering the planet Pluto in January, 1930.

CLYDE W. TOMBAUGH (*left*) OF THE FLIGHT DETERMINATION LABORATORY, WSPG, GUEST SPEAKER, AND EDWARD T. MUNNELL, PRESIDENT OF THE NEW MEXICO-WEST TEXAS SECTION, AT THE SECTION'S MEETING ON OCT. 30, 1952

After presenting the question, "Is There Life on Other Planets?" Mr. Tombaugh gave an extensive analysis of the known facts about the planets of the solar system, dwelling on the theoretical studies of their origin, structure, physical conditions, and anticipated environment. There appears to be no vegetation on the surface of Mars, he stated, as evidenced by the seasonal changes observed on the planet. Venus, on the other hand, seems to be a dust bowl with the possibilities of life there very slim. The outer planets, Jupiter, Saturn, Uranus, and Neptune, have heavy atmospheres of methane, ammonia, and hydrogen existing in various conditions at and near their triple points. Carbon-based life could not exist there, he said, in the tremendous extremes of temperature and pressures. Since Pluto is so small, extremely cold, and possesses little or no atmosphere, prospect of life there seems utterly hopeless.

Judging by the data we have today, Mr. Tombaugh concluded, man cannot expect to find intelligent life, as we know it, in our solar system.

Banquet and Closed Meeting

On Tuesday evening, November 20, 1952, the New Mexico-West Texas Section held a banquet and closed meeting at Vonnie Lee's Tea Room, Las Cruces. N. Mex. The meeting was highlighted by a talk given by Milton Rosen, Viking Project Chief, Naval Research Laboratory, Washington, D. C., who discussed "A Down-to-Earth Approach to Space Travel."

In direct contrast to the current publicity given the artificial satellite and other space conquest programs, Mr. Rosen emphasized the realistic problems facing rocket engineers, and went on to stress the drastic need for more basic research in all fields related to rocketry. Such projects as are now being proposed could not be accomplished overnight, as the public is being led to believe, he remarked. It would be unwise at this time, the speaker continued, for the federal government to make multibillion-dollar investments in space projects. Should a single major failure occur, or a path of development prove to be unsuccessful, he said, all future projects would face serious opposition and financial restrictions. We need time, Mr. Rosen said in conclusion. We cannot work miracles overnight.

Princeton Group of ARS New York Section Holds Charter Meeting

ON November 25, 1952, the newly formed Princeton Group of the ARS New York Section held its charter meeting in the De Long Room, Firestone Library, Princeton University, Princeton, N. J. The meeting was opened by J. V. Charyk, who welcomed the 72 members and visitors. Dr. Charyk then explained the objectives of the Society and introduced Mr. J. P. Layton, vice-chairman of the Princeton Group and one of its chief organizers.

Mr. Layton told of the reasons for forming a sub-section in the Princeton area, and discussed the manner in which this group's activities would supplement the academic program of seminars and lectures. Dr. Charyk then introduced the following officers and Advisory Council members who have been elected to serve until May 1953: *Chairman*, J. V. Charyk; *Vice-Chairman*, J. P. Layton; *Secretary-Treasurer*, G. B. Matthews; *Advisory Council*, L. Crocco, M. Summerfield, and D. C. Sayre.

Mr. Lee Bregenzer, retiring president of the New York Section, then extended greetings and presented the official charter to Dr. Charyk.

C. W. Chillson Discusses Nuclear Rockets

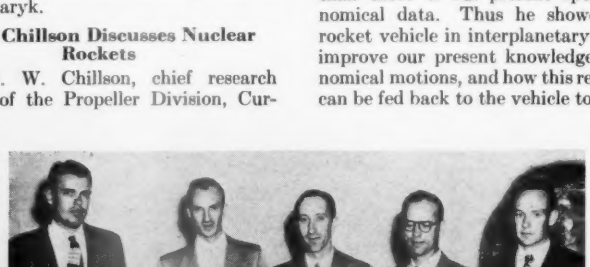
Mr. C. W. Chillson, chief research engineer of the Propeller Division, Curtiss-Wright Corporation, and retiring president of the ARS, presented a short talk entitled "How About Nuclear Rockets?" He listed the major advantages and disadvantages of four general schemes resulting from atomic fission processes: (1) the fission fragment rocket, (2) the radiation rocket, (3) the charged particle rocket, and (4) the neutral particle rocket. The most promising of these, he suggested, is the neutral particle rocket in which some working fluid is heated by an atomic pile and discharged through a nozzle. All four types, he said, suffer from the problems of radiation shielding and excessive weights, and other problems are large cooling or radiating surfaces, heavy structural requirements, and high temperatures.

After all weight requirements were met, Mr. Chillson stated, the possibility of using nuclear energy from fission processes does not offer the tremendous improvements that might be expected from comparison with applications of such energy sources to stationary power plants. Chemically fueled rockets, Mr. Chillson suggested in conclusion, would reach the moon before atomic-powered vehicles left the earth.

Golay Talks on Radio Interferometry

Dr. M. J. E. Golay, chief scientist, Squier Signal Laboratory, Fort Monmouth, N. J., next spoke on the subject of "Radio Interferometry in its Application to Interplanetary Rocket Guidance."

Dr. Golay introduced his topic by pointing out the relative importance of the moon, Venus, and Mars as astronomical observatories and stations for spatial colonization. He discussed the possible trajectories for one-way and round-trip voyages to Mars, stressing the extreme accuracies required in the control of vehicle velocities and positions to insure satisfactory trajectories and landings. He explained how the use of interference techniques on radio signals (received by the rocket from a number of earth stations and retransmitted to earth) can provide these required accuracies, which are actually much greater than those of our present optical astronomical data. Thus he showed how a rocket vehicle in interplanetary flight can improve our present knowledge of astronomical motions, and how this revised data can be fed back to the vehicle to give even



AT THE NEW MEXICO-WEST TEXAS SECTION MEETING, NOV. 20, 1952

Left to right: Edward E. Francisco, Jr., secretary; Robert B. Bolles, vice-president; Milton Rosen, Viking Project Chief, Naval Research Laboratory, guest speaker; Edward T. Munnell, president; and Lawrence W. Gardenhire, chairman, Program Committee.

better control of its flight path. Dr. Golay pointed out as well the difficulties which might be encountered, particularly in obtaining a desirable signal-to-noise ratio, noting how these would limit the allowable broadcast band and also determine the size of transmitters required.

Northeastern New York Section Has Successful Meetings

SINCE its installation meeting in May 1952, the Northeastern New York Section of the American Rocket Society has held four highly successful meetings which were well attended and included lively discussion periods.

In September 1952, Neil P. Bailey, head of the Mechanical Engineering Department, Rensselaer Polytechnic Institute, lectured on "Thermodynamic Processes." Professor Bailey discussed some of the material soon to be published by him.

The most successful meeting was a panel discussion on space flight, held in October. Members of the panel were A. Adamson, R. Haviland, and G. Moore of the General Electric Company's Guided Missile Project, S. Horwitz of Albany Medical College, and R. Johnson, president of the Schenectady Astronomy Club. J. Stokeley of the General Electric Research Laboratory, acted as moderator. The formal title of the discussion was "The Future and Problems of Space Flight."

In November, Edward Scharres and Richard Goldman of the General Electric Company's Guided Missile Project, discussed a guided missile as a servomechanism system. A discussion of a simple servomechanism followed the lecture.

The meeting in December featured Guenter Loeser, vice-president, International Astronautics Federation. Dr. Loeser spoke on the activities of the Third IAF Congress which was held in Stuttgart, Germany, Sept. 1–6, 1952. He also told of the formation of the IAF.

Chicago ARS Group Holds First Meeting

THE first formative meeting of the embryonic Chicago Section of the American Rocket Society was held at the Chicago Engineers' Club, Chicago, Ill., on Dec. 1, 1952. Forty-six ARS members and visitors attended this first meeting, and it is expected that this group will become a very active nucleus for the Society's work in the Middle West.

The following temporary officers were elected at this meeting: *Chairman*, Kenneth H. Jacobs; *Secretary*, D. J. Ljubenko; *Nominating Committee:* Clark E. Thorp, *Chairman*, Victor W. Adams, D. R. Carmody, William A. Casler, and Fred F. DeMuth; *By-Laws Committee:* Robert Gartin, *Chairman*, C. E. Gottschalk and Evan Mayerle; *Membership and Program Committee:* William Skibbe, *Chairman*, Vincent Cushing, C. Harris, E. A. Maynard, and Severin Raynor.

The next meeting for the Chicago group is scheduled for late January, and a formal program dealing with some phase of rocketry will be presented. At that time the By-Laws Committee plans to have a satisfactory proposal prepared to submit to the National Board of Directors for approval.

ARS Participates in IAS 21st Annual Meeting

THE Institute of the Aeronautical Sciences will hold its 21st Annual Meeting from January 26 through January 29, 1953, at the Hotel Astor, New York, N. Y. A program of fourteen technical sessions is planned in co-operation with seven other engineering groups: The American Rocket Society, Institute of Radio Engineers, Institute of Navigation, Radio Technical Commission for Aeronautics, American Meteorological Society, Daniel and Florence Guggenheim Aviation Safety Center at Cornell University, and the American Helicopter Society. The four-day schedule will be concerned with such subjects as flight propulsion, aircraft design, rocket propulsion, aerodynamics, electronics in aviation, meteorology, electronics, aviation medicine, motorless flight, air transport safety, and rotating wing aircraft.

Members of the American Rocket Society will be particularly interested in the ARS-IAS joint rocket propulsion session to be held on Monday, January 26. The program is as follows:

2:00 p.m.–5:00 p.m. Chairman, *F. C. Durant, III*, President, American Rocket Society.

"The Effect of Fluid Properties on the Spray Formed by Two Impinging Jets" by *M. F. Heidmann* and *R. J. Priem*, NACA Lewis Flight Propulsion Laboartory.

"Optical Scanning Techniques for Orbital Vehicles" by *Kurt R. Stehling*, Bell Aircraft Corporation.

"Measurements in Rocket Engine Testing" by *Howland B. Jones, Jr.*, Reaction Motors, Inc.

Washington-Baltimore Section Elects Officers for 1953

A MEETING was held by the ARS Washington-Baltimore Section on Nov. 21, 1952, at the Enoch Pratt Library, Baltimore, Md., for the purpose of announcing the winning candidates to hold office in 1953.

The following officers were elected: *President*, William A. Webb, project engineer, Aircraft Armaments, Inc.; *Vice-President* (Baltimore), Ivan E. Tuhy, Glenn L. Martin Company; *Vice-President* (Washington), Walter L. Webster, Navy Bureau of Aeronautics; *Secretary*, Marvin Hobbs, Raytheon Television and Radio Corporation; *Treasurer*, Charles F. Marsh, U. S. Government; *Directors* (3 years), Harry J. Archer, Naval Ordnance Laboratory, and Joel M. Jacobson, Aircraft Armaments, Inc.; (2 years), Colin M. Hudson, Department of the Army, and Sears Williams, Glenn L. Martin Company; (1 year), Andrew G. Haley, Haley and Doty, Milton W. Rosen, Naval Research Laboratory, and John R. Youngquist, Glenn L. Martin Company.

Three Papers Presented at Southern California Section Meeting

A WELL-ATTENDED and interesting dinner meeting was held by the Southern California Section on November 19, 1952, at the Pasadena Athletic Club, Pasadena, Calif.

Three papers were presented which were received with great interest. "The Use of Plastics in Rocket Engines" was the topic discussed by B. Mundell of Aerojet Engineering Corporation. William T. Skene of North American Aviation, Inc., gave a talk on "Some Problems in the Applications of Titanium for Missile Structure." Frank Brown, Jr., presented his paper on "Theory of Refractories."

At a previous meeting, when two papers, "Problems in Engineering Supervision" by A. L. Stanley of Hughes Aircraft, and "Human Relations in a Research Organization" by F. L. Graham of North American Aviation, Inc., were given, a questionnaire on the desirability of such subject matter was submitted. Results available at the November 19 meeting showed that approximately 72 per cent of the attendance considered the subject far above average in importance.

Nominating Committee Appointed

At the November 19 meeting a nominating committee was appointed to select officers for the year 1953. The committee consisted of the following: Richard Canright, Douglas Aircraft; E. G. Crofut, Aerolab Development Company; Robert Lodge, North American Aviation, Inc.,; Dwight Baker; JPL, CalTech and H. L. Coplen, Jr., Aerojet Engineering Corp.

Sutton and Seifert Speak at Dec. 11 Meeting

Over 200 ARS members and guests attended the dinner meeting on December 11, 1952, held at the Pasadena Athletic Club, to hear papers given by George P. Sutton of North American Aviation, Inc., and H. S. Seifert of JPL, CalTech.

"Rockets Behind the Iron Curtain," the paper presented by Mr. Sutton, provided an interesting aspect of the possibilities of espionage by scientists. Mr. Sutton's hobby is to deduce from various technical papers and comments from abroad the direction of research and projection as to what is being accomplished and why. From the speculations brought forth by Mr. Sutton and based on his analysis, the picture is not encouraging.

"The Effect of Variation of Propellant Density on Rocket Performance" by Dr. Seifert, posed two separate problems:

The first problem is, given a rocket with prescribed empty weight and propellant volume as well as propellants with known physical and chemical characteristics, to determine the relative proportion of each propellant that must be carried by the rockets for maximum burned velocity, assuming constant conditions during burning.

The second problem is analogous to the first except that a variation in mixture ratio during burning is permitted. The first problem is solved by elementary calculus; the second reduces to one in the calculus of variations.

Technical Literature Digest

H. S. SEIFERT, California Institute of Technology, *Associate Editor*

CONTRIBUTORS: D. Altman, D. I. Baker, R. B. Canright, F. C. Gunther, H. S. Seifert, F. H. Wright

Book Reviews

DAS MARSPROJEKT, STUDIE EINER INTERPLANETARISCHEN EXPEDITION (in German), by W. von Braun, Umschau Verlag, Frankfurt am Main, 1952, 82 pp., 9 illus., 36 tables.

Reviewed by G. P. SUTTON
North American Aviation, Inc.

The recent popular talks and articles on space travel by Dr. von Braun are based on serious and intensive engineering calculations. This booklet gives the basic assumptions, the fundamental methods, the mathematical relations, and the numerical values used in determining the size, weight, trajectory, shape, and many other technical features of a specific set of space ships. The author visualizes an expedition of ten space ships, which leave from a satellite space station and travel to Mars. There they are maneuvered into a floating-satellite orbit course around the planet and remain until the return trip to earth is started. From these orbiting ships, three special landing craft are launched and land on the surface of Mars. Two of these three landing craft are remodeled and returned to the space ships. Seven of the original ten space ships then attempt a return to the earth satellite station. Three basic types of space vehicles are investigated in this report in considerable detail, namely, (1) a three-step rocket used to transfer personnel and equipment between the earth and the satellite station, (2) the space ships for traveling from the earth satellite station to the Mars satellite orbit, and (3) the landing craft for the travel between the Mars satellite orbit and the planet's surface. The booklet also contains sections on rough estimates of the over-all effort, of interplanetary radio communications, and of rocket-efficiency calculations.

The purpose of the calculations in this book is to show that space travel to Mars is feasible and can be visualized with today's knowledge of rockets and missiles. It explains that such an expedition, to be practical and successful, requires the use of several space ships and crews totaling 70 men. It also claims that the total effort of such a space trip does not exceed that of a limited local military war operation.

To the best of this reviewer's knowledge, this is the first coherent set of calculations and relations presented on space-ship design and trajectories.

AIRCRAFT JET POWERPLANTS, by Franklin P. Durham, Prentice-Hall, Inc., New York, N. Y., 1951, ix + 326 pp.

Reviewed by C. C. Ross
Aerojet Engineering Corp.

This book was written primarily as a text for undergraduates in aeronautical engineering courses. The book is well written and reads easily. It is a desirable reference for engineers both in the jet propulsion field and for those closely associated who may have occasion to refresh their memories on fundamentals or design principles. It is the first book of this type to discuss the principles of afterburners and ramjets.

The first chapter is devoted to a brief description of the general characteristics of the various power plant types, together with a listing of definitions and standard nomenclature. Chapters 2 and 3 review the fundamental thermodynamics necessary to an understanding of jet-propulsion principles. Chapters 4, 5, and 6 describe the engine processes and performance analysis of the turbojet, turbojet plus afterburner, and the turbopropeller. Chapters 7, 8, 9, 10 and 11 are devoted to the fundamentals of gas-turbine components: the diffuser, air compressors, combustion chambers, turbines, and nozzles. Chapters 12 and 13 describe the ramjet and the rocket. The ramjet discussion includes a review of the fundamentals involved in shock waves with particular reference to ramjet inlets. The chapter on rockets is short but describes the process adequately for the beginner. Each chapter is concluded with a series of problems designed to check the reader's understanding of the text. Answers are not given.

The book should provide an excellent introductory course to the student, as well as a ready reference to the practicing engineer for the fundamental equations and their development.

MECHANICS OF THE GYROSCOPE, by R. F. Deimel, Dover Publications, Inc., New York, N. Y., 1952, 208 pp. cloth $3, paper $1.60.

Reviewed by L. DAVIS, JR.
California Institute of Technology

The subtitle of this book, The Dynamics of Rotation, is an appropriate description of its contents. The first three chapters give a brief summary of dynamics based on Newton's equations and the law that the rate of change of angular momentum equals the applied torque. Lagrange's equations and vectors are not used. The remaining seven chapters treat a variety of devices ranging from simple gyroscopes and tops, through rolling coins and spinning eggs, to the gyro-compass, the ship stabilizer, and the monorail car.

The reader will need to be familiar with calculus and simple differential equations and will find the going easier if, independently of the summary given by the author, he understands the basic mechanical laws used. The author intends that students should "get a real insight into them as a by-product of working at the harder parts." He seems very successful at treating the various rotational phenomena quantitatively without using advanced mathematics or losing track of the physics of the situation. Since the text is essentially unchanged from the first edition in 1929, there is no detailed description of modern apparatus. This is not a serious defect since the emphasis is on physical principles rather than structural features. The reader should be able to apply the results and methods to any particular system of interest to him.

The publishers are to be congratulated on making available such an inexpensive paper-bound edition. It should thus appeal to anyone having even a minor interest in the topics treated.

THE EARTH'S MAGNETISM, by S. Chapman. John Wiley & Sons, Inc., New York, N. Y., 1951, 127 pp. $1.50.

Reviewed by W. H. PICKERING
California Institute of Technology
Jet Propulsion Laboratory

This well-known little book is one of Methuen's monographs on physical subjects but is somewhat more technical in content than are most of the others in the series. It is a second edition of a book which first appeared in 1936. Professor Chapman has evidently revised the text rather thoroughly and has brought the contents completely up to date.

Within recent years, interest in terrestrial magnetism has arisen in new fields of science and technology; e.g., new problems in navigation, effects on radio transmission, new methods of prospecting. In all of these fields a knowledge of terrestrial magnetic phenomena has exerted a direct influence on technological applications.

The technical worker who needs an introduction to the subject will find this

EDITOR'S NOTE: This collection of references is not intended to be comprehensive, but is rather a selection of the most significant and stimulating papers which have come to the attention of the contributors. The readers will understand that a considerable body of literature is unavailable because of security restrictions. We invite contributions to this department of references which have not come to our attention, as well as comment on how the department may better serve its function of providing leads to the jet propulsion applications of many diverse fields of knowledge.

book very valuable. It is brief but contains a great deal of factual information. Without giving details of the instruments used, Chapman presents the nature of the experimental data which have been accumulated and the manner in which they have been analyzed. He touches briefly on the theoretical explanations which have been advanced to explain both the internal and the external parts of the magnetic field. He suggests some of the problems which remain unanswered and provides a list of references for further study.

It is evident that experimental data from very great altitudes would be a valuable addition to our knowledge of the earth's magnetism; thus it is hoped that the members of the ARS keep conversant with this subject. Chapman's book is ideal for the purpose and deserves a place on every bookshelf.

HIGH-ENERGY PARTICLES, by B. Rossi, Prentice-Hall, Inc., New York, N. Y., 1952, 569 pp. $12.50.

Reviewed by R. F. CHRISTY
California Institute of Technology

Students, teachers, and research workers in modern physics will welcome this book on high-energy particles by one of the outstanding experimentalists in the field. The primary emphasis is on the behavior of high-energy particles both in cosmic rays and from accelerators. The discussion of cosmic-ray phenomena, as such, is reserved for another book which is being prepared by the same author.

An excellent 80-page chapter is devoted to the theoretical description of various basic electromagnetic interactions of charged particles and γ rays. Such a description is, of course, essential in this subject when one realizes that most means of detection, identification, and detailed study of particles are based on these interactions. Another 80-page chapter presents in some detail the theory of cascade showers. Still another chapter discusses the experimental verification of the theory of electromagnetic interactions.

The basic experimental detection methods are discussed from the point of view of the methods and the type of measurements that can be made, but the discussion is not sufficiently detailed to serve as a reference on the techniques. A chapter on the basic experiments leading to the identification and measurement of the fundamental properties of the positron, μ meson, and π mesons, constitutes an excellent review of this subject. The other V, τ, K, etc., particles, which form such a confused picture at present, are mostly too recent to be mentioned. About one third of the book is devoted to reviews of experimental material on the production and interaction of mesons and nucleons at high energy, both from machines and from cosmic rays. This section is accompanied by a very fine collection of photographs of events as seen in photographic plates and in cloud chambers, illustrating beautifully the wealth of phenomena involved.

The time seems right for this book, even though the most recent developments in new particles are necessarily absent. The basic ideas concerning π and μ mesons have been consolidated, whereas the progress on newer particles is slow. This book should be useful for many years to come.

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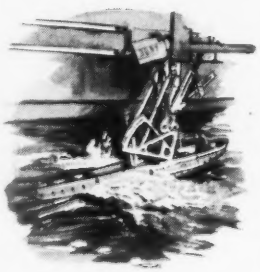

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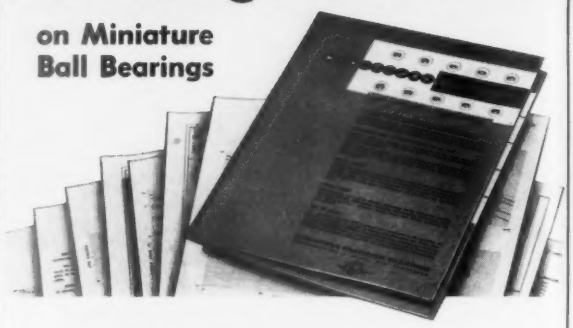

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